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Science, Invention and Society*

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I

IT is no accident that we dance rumbas instead of minuets, for the dance is part of our culture. It is no accident that we ride in automobiles, listen to music broadcast half around the world, have our offices in fifty-story skyscrapers and turn our wheels by electric energy. These, too, are manifestations of our culture.

When we speak of a culture we conjure up a picture of group behavior—of a community or a race influenced by common instincts, passions, motives and interests. A social tension is evident—a tension that compels men to act, dress and think more or less alike. In the Middle Ages social tension expressed itself so strongly in religion that there were more than a hundred religious holidays in the year; a new architecture evolved; and the whole of Europe arose to the spiritual need of wresting Jerusalem from what was regarded as infidel control. If, today, we rush in airplanes through the atmosphere at two hundred miles an hour, talk to one another across the Atlantic Ocean, read two-cent newspapers and determine the chemical and physical constitution of a star by light that left it when dinosaurs shook the ground, it is not because the human mind is intrinsically any better than it was 10,000 years ago, but because it has acquired different interests under social tension. Any kind of tension seeks relief. To a socially tense people relief comes through art, philosophy and science, depending on the crucial need of the epoch.

Waldemar Kaempffert

Anthropologists and social scientists as a class, no longer believe in the "great man" theory of culture—a theory expounded by Carlyle in his *Heroes and Hero Worship.* Great men do not of themselves produce cultures, nor do cultures necessarily produce great men. In every race there are leaders—strong, gifted per-

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sonalities that respond more sensitively to social tension. Hence Dante, Shakespeare, Voltaire, Bach, Newton, Watt, Morse, Bell, Edison, Marconi and Einstein must be regarded as fuses that blow out and that enable society to short-circuit itself and follow the lines of least resistance. Generally, neither society nor its leaders are aware of the process.

II

When we say that "the time is ripe" for the appearance of a work of art, a scientific discovery, or an invention, we merely mean that social tension at last seeks relief. There was no technical reason why an ancient Greek should not have invented the hot-air balloon. All that he needed was a fairly dense fabric, a basket and a fire. The materials were available 10,000 years ago. A Greek simply did not think in this fashion, because the social circumstances were not of the kind that stimulate technical thinking. Experimenting and inventing held little interest for him. On the other hand our instruments for measuring the velocity of light could not have been devised by an ancient Greek. He did not think of light as we do. In fact he did not know that it had a velocity.

A change came over our group aspirations about the middle of the eighteenth century. That is, we became aware of a new impetus. What we call the objective, scientific point of view began to be taken toward the universe, which means that we had succeeded in partially divorcing our feelings and traditions from our perceptions, and we proceeded to interpret sticks and stones and stars dispassionately. Professor Whitehead calls this mode of approach "the most intimate change in outlook that the human race has yet encountered." Lewis Mumford has shown in his admirable and scholarly *Technics and Civilization* that, contrary to general teaching, there never was a time in the period covered by recorded human history when men did not seek to explain the cosmos scientifically and when they did not invent machines. But "science" and "the machine" are modern conceptions. If economists have spoken of the Industrial Revolution and dated it roughly from the introduction of factories, machines and patent systems after the development of textile inventions and the steam engine, they have misled us. What seemed like a rapid flowering of science and invention in the late eighteenth century was merely the evidence of an accelerated adoption of a viewpoint. The yeast that had been fermenting ever since there were wondering and thinking men at last leavened the whole mass of western society.

III

The wave of scientific investigation and mechanical invention that sets our time apart was confined to no one country. It swept over western Europe. Since the New World was settled by western Europeans, it necessarily included the United States. We must deal with it, not nationally, but socially. There is something childish about Englishmen, Frenchmen, Germans and Americans, who claim for one of their countrymen the honor of having invented the "first" electric lamp or the "first" dynamo or the "first" telegraph. There are very few "first" inventions and among these are the wheel, the bow and arrow, the bow-drill, and fire-kindling instruments—all of which must be credited to unknown, prehistoric, savage Edisons. Every invention is rooted in old principles, and every inventor has a technical heritage without which he could not progress. Edison certainly could not have invented the carbon incandescent lamp had he been a Cro-Magnon man in southern France 50,000 years ago. Without Galvani, Volta, Faraday and Henry, the telegraph of Morse would never have been conceived.

That social tension and technical heritage are indeed the well-springs of science and engineering has been clearly demonstrated by Professor William F. Ogburn. With Dr. Dorothy Thomas he compiled a list of one hundred and forty-five major inventions and scientific discoveries all of which were made by different men independently and simultaneously. Thus Newton and Leibniz independently devised differential and integral calculus; Wallace and Darwin simultaneously hit upon natural selection and the survival of the fittest to explain the origin of species; Gray and Bell filed patent applications for the telephone on the same day, and both were quite ignorant of the efforts that Reis, a German, was making to talk over a wire. Professor Ogburn confined

himself to one hundred and forty-five major innovations. Had he also gone to the needless trouble of examining thousands of lesser technical advances he would have written a book of a thousand pages. Every patent lawyer knows that the applications which he files on behalf of his inventive clients must invariably be amended to meet the references of the Patent Office to similar disclosures in technical literature.

IV

At times it seems as though the character of scientific research and invention has something national about it. Thus Germans have made a brilliant record in chemistry and Americans in mechanical invention. But this is exactly what may be expected when we consider the social and economic environment. Germany is not rich in natural resources. She must make the most of materials. Hence the exploitation of coal tar, and the rise of chemistry. We, on the other hand, were long deficient in labor, but rich in natural resources. Hence we have been the great inventors of labor-saving devices. As our population grew the old differences disappeared. Now our achievements in chemistry equal those of the Germans. In other words, the kind of economic and social community in which we live determines the kind of scientific research and the kind of invention on which we embark. By this I do not mean to perpetuate the old myth that necessity is the mother of invention. It isn't. An inventor in the right environment can no more help inventing than an artist can help painting pictures. What is invented has its roots quite as much in what may be called the soul of the environment as in its material opportunities.

In the old days the inventor worked alone in a garret. Sometimes he was aided financially by some capitalist who believed in him. Usually he lived precariously on his own resources. Compelled to compete with organized research as it is conducted in the industrial laboratory, the outside "heroic" inventor who works picturesquely in solitude is disappearing. Edison may prove to have been the last and greatest of the type. If the heroic inventor survives at all he is almost certain to be a trained physicist or engineer rather than an empiricist, who, like Goodyear, patiently and inspirationally performs ten thousand experiments before at last he achieves the vulcanization of rubber.

Until the coming of the steam engine it mattered little industrially whether a country possessed coal deposits. After James Watt, coal was potential energy that could be released to produce goods. Nations were willing to fight for it. The regions where coal was abundant became the seats of industry. Those that had no coal sought salvation in water power both before and after the electric generator was developed. At first the steam engine could be utilized only near the mine or near a navigable stream on which coal could be transported in bulk. Later the railroad made it possible to establish industries based on steam farther from the mine. But not too far.

The distance to which power can be transmitted by a steam engine directly is limited to a few feet by a belt or a rope. As a result the engine had to be used individualistically. That is, every factory generated and distributed its own energy. By 1930 some 270,000 individualistically operated steam engines were running in the United States. To these must be added 53,000 individualistically operated steam locomotives which haul more coal by weight than they do wheat, corn, oats, hay, lumber, steel and iron combined—haul energy in the form of solid, black lumps, largely for their own consumption.

When Edison built the first central station in 1881 this picture was destined to change. Energy in the form of electricity became free. It can now be flashed hither and thither for about 250 miles. Not only this, but central stations can be interconnected so that a few of colossal size can take the place of many. Thus regional power pools can be created which can be tapped wherever land is cheap, railways and waterways are at hand and labor is reasonably abundant. After James Watt, workers flocked to the steam engine; after interconnection, electricity could be flashed to the workers wherever they might be.

What we have, then, is a definite trend to the collectivistic use of energy generated in a few centers. There is nothing accidental about this. The engineers of the great utility companies have for years kept this goal in view. So has every important government.

V

If the introduction of the steam engine is one of the factors that brought about the Industrial Revolution, then the advent of electric energy marks a second revolution destined to have far-reaching consequences. I do not mean merely electrified farms and households, with Muscle Shoals and Niagara Falls milking the cows and sucking out dirt from the carpet by way of a vacuum cleaner, but a profounder change which may affect the very nature of government and society, as we shall see. Electric energy has become like water or gas—something that steam energy could never become.

The introduction of the steam engine gave an enormous impetus to invention. Before Watt's day engines were used only to pump water out of mines. Watt made an engine of the old pump. After that any machine could be driven by steam. The opportunity was seized quickly enough. Machines were invented to build other machines, and thus a process of reproduction was inaugurated that seems appalling to some sociologists and romantically captivating to others. The countless machines that do the work of hauling, lifting, pressing, punching, boring, folding, twisting, cutting and bending are all highly specialized, artificial organisms. Industrial processes are carried out, for the most part, by tireless automata which are nothing but extensions of human muscles and human senses controlled by the human brain. What we have here is something much more important than the subdivision of labor. Skill and intelligence have, in part, been transferred to the machine.

Mass production means standardization. It means that we must dress more or less alike, ride in automobiles that are more or less alike, see at night by lamps that are alike, live in houses that resemble one another in their comforts and mechanical conveniences, eat canned and packaged foods that are distributed to millions with like tastes. There is hardly a human activity that is not influenced in some way by the machine—by mass production. The farmer who cultivates a few hundred acres is a mass producer, thanks to his tractor, his mechanical planters, reapers, and harvesters. Even our emotional cravings are satisfied by motion pictures, which are intended for the masses.

Mass production on this scale implies control—organization. The need of organization was recognized from the first. A man like Arkwright, inventor of important spinning machinery, organized his mills after a fashion that commands admiration even at this late day. But let me emphasize the need of the expert who plans the organization and controls it. Without him there is only chaos.

When mass production finally reaches a point where molten pig iron is poured at the rate of thousands of tons a day and automobiles are produced by the million every year, the need for more organization, more control arises. Out of this need came what is known as Taylorism in Europe and scientific management in America.

Machines have always been arranged with an eye to their general relations to one another. But before Taylor there was no scientific coordination of machines and their tenders. He converted the factory itself into a colossal machine. Taylor and his followers integrated machines and men and transformed the living muscles and the steel wheels of a factory into one huge mechanism that could be managed by a superexpert—the president of a corporation.

Note in all this the increasing organization of industry as it becomes more highly mechanized and the need of directing experts. The worker knows only the name of the part he places in a machine. He is simply operator number twenty-five, and his job is to turn out daily two or three thousand bolts numbered two hundred and thirty-one in a contrivance that becomes an automobile or a locomotive. A few engineers, the experts at the top, alone see the mill and its product as a whole. Without them despite the tremendous problem which they face today of winning the confidence and cooperation of the workers, labor would be helpless. The point is of some importance in considering the trend in government, as we shall see.

I do not know how many experts actually control our processes of production and our banks and other financial institutions. Probably their number is not more than a million in the whole world—less than one percent of the civilized population. From them come the new inventions and the new methods of financing industrial enterprises. It is they who run the

world. If some deadly disease were to afflict them simultaneously, we would die of starvation and thirst or some pestilence. It is probable that science and engineering are now creating a new social class more important than any other—the men who understand energy and its application. Once upon a time it was thought that only the military nobles and later that only the moneyed class were fit to rule. Now it seems as if only the scientific expert is fit to rule.

VI

Thus far I have dwelt only on the technical aspects of society. But the rise of the machine and of mass production also has its economic consequences. The modern corporation appears. So does the combination of corporations—the trust. Out of the machine comes the trust. There was no sense in combining factories of hand-workers. Production costs could hardly be lowered. But there was much sense in massing machines for producing identical pigs of iron, or identical cans of tomatoes, or identical shoes. Thereafter single machines could be made to do the work of a dozen. In a General Motors factory you may see a hydraulic press stamping out fenders for automobiles. It costs at least $150,000. It does the work of perhaps six smaller presses. It would stand idle half the time unless the output were large enough. With a sufficiently large output it dispenses, not only with six smaller machines, but with five crews. Six small automobile factories would have to combine to make the most of that $150,000 hydraulic press and produce fenders at the lowest possible cost.

With mass production and massed factories or trusts we have entirely new financial and economic problems. Banking has had to adapt itself to the machine. So has economic theory. And again we behold the expert in control, the expert in economics, although he is by no means as sure of his methods and by no means as able to predict results as the expert in charge of production.

VII

The whole trend of society for about one hundred and fifty years is now clear. We see energy supplanting muscle in manufacturing; machine after machine appearing; mass production standardizing life; ships and railroads becoming mass carriers; the machine so far dominating industry that invention becomes a recognized profession, with group invention taking the place of inspirational, individual, "heroic" inventors; the standardization of goods as a result of mass production; the gradual abandonment of thousands of individualistically operated steam engines for a few central stations that transmit electric energy over vast regions; electrical communication, designed from the outset for mass utilization; mass production, for whatever purpose, demanding and receiving more and more organization; and a handful of experts controlling the machinery of modern civilization.

When we behold industries thus expanding until they enmesh, not only a whole country, but the world, and also when we behold oil, coal, the production of necessities in the hands of a few financiers and technical experts, the need of government control to prevent exploitation merely for the sake of profits is evident. Almost from the first, national or local governments have realized the necessity of either owning or controlling such activities as the carrying of mail, the supplying of communities with water, gas and electricity, and the means of telegraphing and telephoning. Now there are signs that the production and distribution of goods must be similarly supervised and regulated. Either the expertly managed industries must run the government, or the government the industries. In a word the mechanism of mass production so vitally affects the masses that they are possessed by a vague fear of slipping back into something worse than serfdom. They sense the need of a change in government.

Science, invention, mechanized industries mean technical competence. But we do not know what competence in government means because we do not agree on forms of government. We do agree on competence, and competence is impossible without experts.

If the government must intervene, which seems inevitable, it is clear that it must adapt itself to the exigencies of managing mass producers, mass carriers, mass conveyors of intelligence by telephone, telegraphs and radio, mass trade, mass credit and mass banking. It must have a different

organization. It must rely, not on politicians, but on experts. To order industrial and financial experts what they should do requires the knowledge of experts. Politics must consider technics rather than emotions.

This clearly means more organization than we have now. It means more control and not less. It means planning, not to meet the exigencies of a depression, but planning for the future. Unless there is planning there is no opportunity for social invention. Social invention must become as systematic and as well organized as mechanical invention and scientific discovery if it is to keep pace with the laboratory. The point has been reached when we can no longer make the utmost use of scientific and mechanical innovations without social adjustments and social invention. The alternative is a slowing down of mechanical invention, something recognized in the often expressed proposal that there shall be a temporary halt of scientific and industrial research. No engineer, no statesman has yet seriously considered such a recession. Professor Dewey puts it well when he says:

> "The depression is a small price to pay if it induces men to think about the cause of the disorder and the confusion and insecurity of our time. It seems incredible that men who have brought the technique of applied physical discovery, invention and use to such a pitch of perfection will abdicate in face of the infinitely more important human problem."

Perhaps this restlessness, this sense of insecurity, is a favorable omen. Whitehead maintains that the great ages of the past have always been unstable ages, although instability may threaten civilization. To him, it is the business of the future to be dangerous. Progress always involves adventure. It is the merit of science that it equips the future for the task of being adventurous.

VIII

No one knows what form of government will evolve out of the social needs that have come with science and the machine. At present the trend, at least in the surviving democratic countries, seems to be toward collectivism in which private profit will be either severely limited or abolished entirely. Collectivism may take any one of several different forms. It may be a democracy modified to suit a mechanized society, a democracy which will elect to office physicists, chemists, engineers, economists, physiologists, experts familiar with the design and operation of machines, production and consumption, credits, money, human appetites and needs; it may be communism or socialism or fascism. Whatever it may be, that government must of necessity be a government by technicians, by experts.

With a world that is becoming more and more collectivistic, that demands more and more organization and more and more expert control, it is clear that democracy must change its character if it is to survive at all. It is a purely political conception that had its birth in eighteenth century ideals of liberty, equality and fraternity. A mechanized society, dependent on creative physicists and engineers, on organizers, on experts in technics as well as finance must adapt itself to less individual liberty in order to preserve fraternity and equality of opportunity. Democracy wears periwigs and knee-breeches, writes with quill pens, and thinks of political parties and political control. A mechanized society wears standardized, machine-made clothes, writes on typewriters, and should be ruled more by industrial and economic organizations than by political parties.

Whether democracy can survive the increasing strain to which it is being subjected by machine methods and scientific progress no one knows. If it does, it will be vastly different from eighteenth century egalitarianism. We have but to cast our eyes backward to note the trend. There is less personal liberty today than there was a generation ago; there will be still less a generation hence. There will be more and more need of organization, more and more need of integration of workers and machines, more and more need of experts. Fraternity may remain, but conceptions of liberty and equality must change.

Physics in The Paper Industry*

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Introduction

EVERYWHERE we turn we find paper in one form or another. It is on our walls, on our desks and book shelves, in our pockets, around our groceries and freight. In the form of pulp, it is converted into rayon, transparent sheets and photographic films, lacquers, and plastic materials. Without paper there would be few physicists and very little understood physics. Conversely, without physics there would be no paper, for paper making is fundamentally a physical process. And yet this great industry managed to wobble along for about two thousand years without the aid of the physicist, and without apparently missing him. It is a pointed question to ask, what can the physicist do for the paper industry?

This question has point both for the industry and for the physicist. The industry in this country employs only about ten Ph.D.'s in physics to my knowledge. The situation and the question are about the same for the physicist today as they were for the chemist about twenty-five years ago. The chemist is now an established necessity. The engineer was accepted much earlier than the chemist on account of the advent of power driven machinery. Before that papermaking was an art entirely. Physics, however, has contributed right along through the activities of the papermaker, engineer and chemist. The papermaker developed most of the fundamental physical processes essentially as they are today. The engineer brought in the physics of steam and electric power and mechanical machine design, and many measuring instruments. The chemist brought with him a large fund of physical technique, microscopy, photography, and many physical testing methods. Both engineer and chemist are accustomed to profit by developments in physics produced outside of the industry.

The general function of the physicist in the pulp and paper industry is to cooperate with chemists and engineers to maintain and improve the efficiency of manufacture and use of pulp and paper, and to extend the range of usefulness of pulp and paper products and by-products.

We are all familiar with the ways in which physics finds its way into industry unaccompanied by the physicist. We are also familiar in a general way with testing instruments, color measurements, microscopy, x-ray methods of studying the structure of cellulose, and other applications of physics that I might discuss in detail. But I believe that by discussing, without much detail, some of the typical classes of physical problems that confront the industry and demand answers of the *physicist*, a better picture may be obtained of the present and future place of the physicist *within* the industry.

Processes and Fundamentals

Consider a simplified picture of what we must do when we make a sheet of paper. Fundamentally it is this. We take a log of wood composed of fibers which are principally cellulose, held in place by an almost continuous framework of other material which is principally lignin.

* Presented at the Second Conference on Industrial Physics, held by the physics department of the University of Pittsburgh, May 22, 1937.

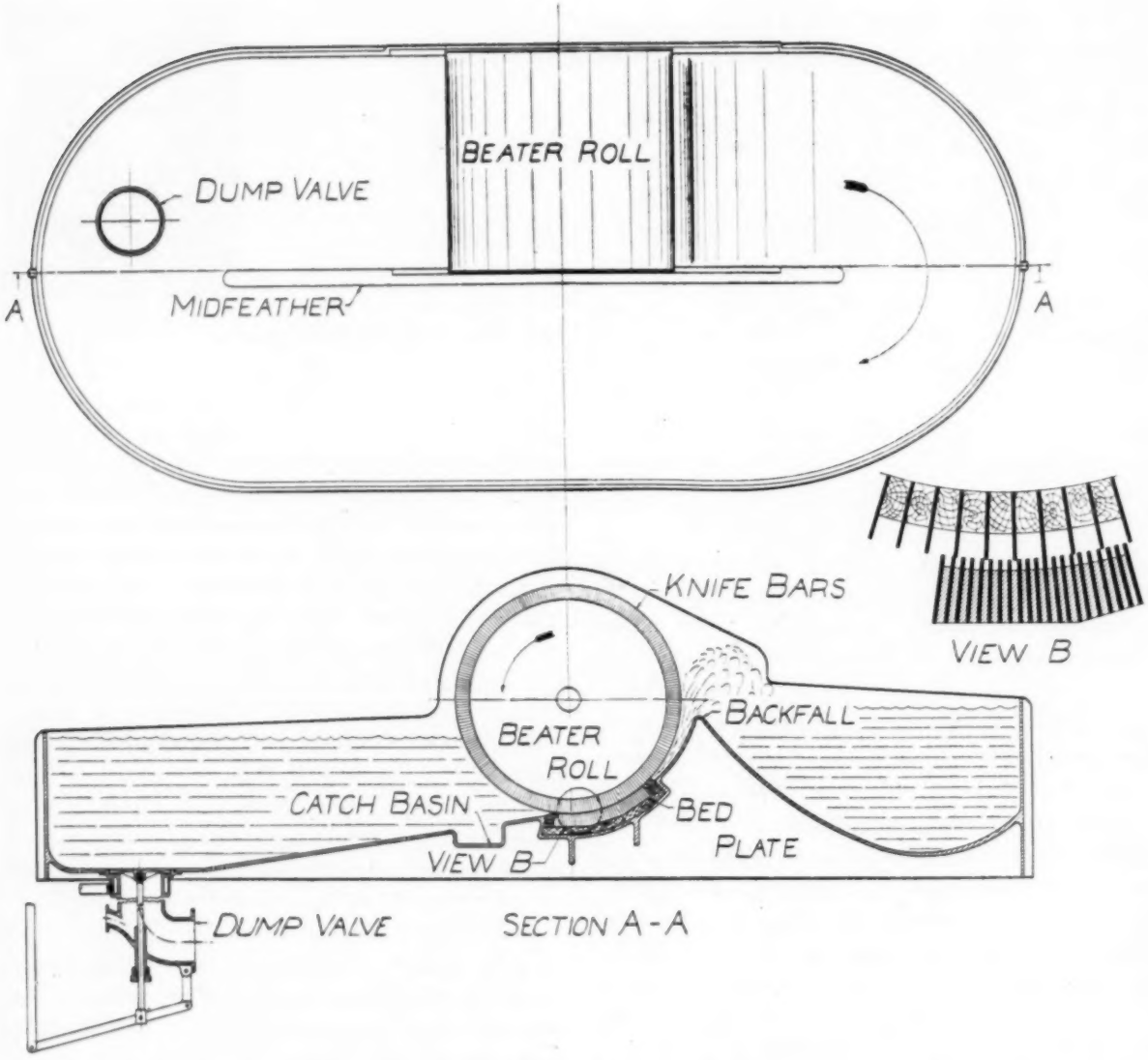


FIG. 1. The Holland beater, used to beat the fibers and thus increase the tensile strength of the final sheet of paper.

We must separate the fibers from this framework and reorganize them into a sheet. The only output of energy that is obviously necessary in this process is to break the cohesion between the components over their surfaces of contact. The rest consists of a reorganization that is purely geometrical, and could perhaps be accomplished by some sort of a Maxwell demon without doing any work. Actually considerable energy is expended in making a sheet of paper, though the work of cohesion itself is probably small. The physical efficiency of the processes of papermaking appears to be very low. This appears again if we examine the fundamental processes. The energy used goes principally into heat or into chemical waste products.

Let us follow this idea of energy conservation through a rough description of some of the processes in a sulphite paper mill. The wood is first cut into chips by a set of knives imbedded in a large fly wheel that rotates at high speed. Most of the energy probably goes into heat. Next, in order to remove the unwanted lignin and other materials the chips are cooked or digested for about thirteen hours at 134 degrees centigrade and seventy-five pounds pressure with

a liquor consisting of calcium and magnesium bisulphites with a large excess of sulphur dioxide, which dissolves the lignin components chemically. This does more than overcome the forces of cohesion. It involves a chemical reaction throughout the volume of the lignin framework. The energy used and the chemicals contained in the spent liquor are largely waste. The undesirable lignin components are now washed out with water, and the fibers are carried in water suspension through a series of screening and settling processes to remove dirt, knots, and uncooked chips, and are bleached to the required whiteness. It must be stated here that in the manufacture of finer grades of paper it is necessary to remove some undesirable constituents from the body of the fiber itself, which must be done chemically.

The next major process is beating, and its nature is indicated by the name. It is necessary to beat the fibers in order to make the sheet of paper hang together. The strength of the sheet is dependent on the strength of the fibers and on the amount of beating they receive. Beating is another process where a considerable amount of energy is used to do relatively little work on the fibers. The commonly used beater (Fig. 1) essentially serves to pass the pulp repeatedly between a large roll and a bedplate the surfaces of which consist of transverse metal strips, the width, spacing and depth varying in different beaters. The action on the pulp is a pounding, scraping, cutting and mixing. Just exactly what happens to the fibers to make them form a strong sheet is not very clearly understood. A fraying effect occurs, which helps the fiber to mat together with other fibers, but it is doubtful whether this adds greatly to the strength. The major factor seems to be a physical reorganization of the materials on the surfaces of the fibers, resulting in the formation of a cement-like bond on drying, but the mechanism is not clear. It probably requires very little energy. The cutting and mixing actions of the beater require very little energy. But considerable energy is used in churning up the ninety-five percent of water that is present in the beater for the period of one to fifteen hours, which may be required for a single batch. A study of the essential functions performed by this machine would very likely lead to a separation of beating, cutting, and mixing, which are all performed inefficiently, also to an increase in efficiency of each of them, and further to production of stronger paper because of less internal damage to the fibers. Beating by high intensity or high frequency sound has been suggested, but not effectively tested. Separate production of cellulose bonding material to be mixed with the pulp instead of beating has also been suggested but not effectively investigated, to my knowledge.

From the beater the stock passes continuously through another continuous beating and cutting machine, is diluted with water and run onto the moving wire screen of the paper machine through which the water is drained leaving a sheet of paper. The sheet then passes through squeeze presses and onto a series of steam heated dryer rolls which accomplish the final stages of drying. In these dryers we again find a process where an excess of energy is used to accomplish the purpose. Theoretically we have merely to perform a geometrical separation of water and fiber. Actually the water is evaporated directly and usually the heat is not recovered, but heat and vapor are both carried away by an air ventilating system. Finally, the paper is passed through a set of heavy rolls which press it and smooth the surface, and wound on a reel for finishing processes.

It is apparent that in these processes there are many places where much greater efficiency could probably be attained. But it must be remembered that in the industrial world efficiency is not energy efficiency, it is cost efficiency, so that cost of machinery and speed are important items. However, in evaluating a process, or a machine design, energy efficiency is an important criterion. It frequently goes hand in hand with simplicity and cost efficiency.

Typical fundamental problems are, what is the theoretical minimum energy requirement for a given process, and what is the essential variation of this energy requirement with speed of the process. Separating solids from liquids and solids from solids are typical processes, and so is the converse problem of mixing materials. Though no energy is obviously required for the mere geometrical displacements, we usually spend a considerable amount, and one might

Hammermill beater room. There are 28 beaters in this room.

ask whether there is any energy required merely to alter the statistical distribution of particles, and how that energy varies with speed of rearrangement. This question has a certain analogy with the thermodynamic problem of converting heat into work, where a loss of energy occurs on account of statistical properties. Where we have solids in liquids, speed of separation or mixing certainly introduces energy losses due to hydrodynamic resistance.

When we ask the ever present question, "Can this process or machine be improved, and how much?," the answer depends on some such examination of the fundamentals of the process. If it cannot be demonstrated that the process has a high order of efficiency in terms of these fundamentals, then a search for improvements is justified, even though we have no immediate clue as to how they are to be attained. Both the examination of processes and the search for improvements are fields for the physicist.

Automatic Control

Next let us make a picture of the general problem of automatic control of processes. Ideally we should like to feed the wood in at one end, set a number of indicators labeled "paper properties," and have the paper appear with those properties at the other end. In the present state of our knowledge perhaps this picture looks fantastic, but again the answer is: if it cannot be proven impossible, the attempt to attain it is justified, and the steps taken have value in themselves.

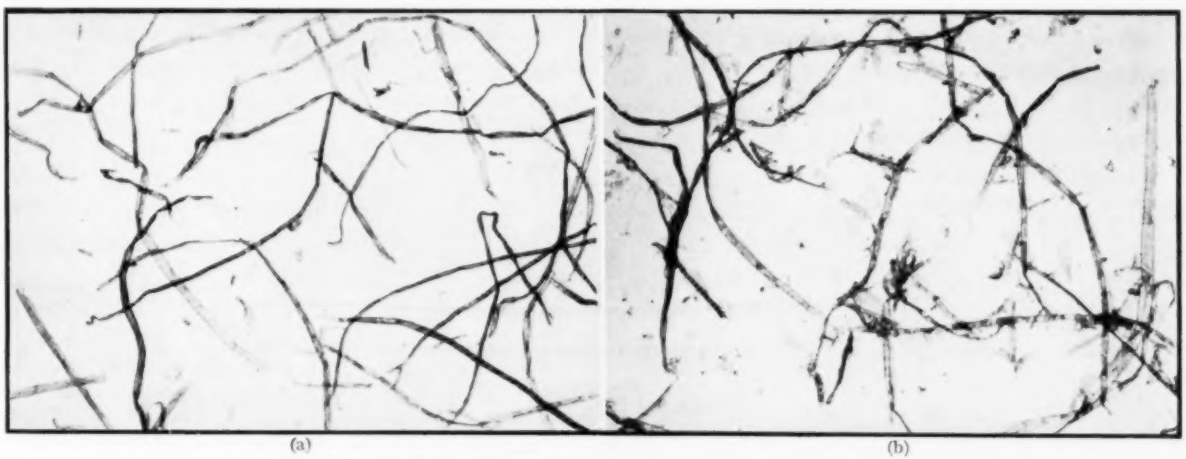
In order to attain automatic control we must solve four classes of problems. First, for control of any kind we must be able to measure *enough* properties of the raw materials, of the pulp at various stages of processing, and of the paper product. Many more or less satisfactory tests and instruments are in use for measuring paper properties such as tensile strength, tearing strength, pop strength, porosity, folding endurance, oil and water penetration, opacity, brightness, gloss, color, formation or look through. Much of the work of physicists in the industry has been devoted to such instrumentation problems. At present very few of the measurements can be made automatically. Second, we must be able to control enough process variables to determine the nature of the paper. I have seen a list of one hundred such variables on the paper machine. Measurement of the variables is necessary and perhaps some reorganization of processes to establish the required number of variables. Third, we must know the fundamental relations between the measured properties and the process variables. In paper and pulp making these relations are of such a nature that most of the variables affect most of the properties. The properties and variables cannot often be separated into pairs that depend only on each other. Where such a separation can be performed even with reasonable approximation the control problem is much simpler, and present controls are limited to this type. An example is moisture control, where

steam in the dryers is controlled to give a constant vapor pressure over the paper. In general it will be necessary to solve problems of the fourth class, which is to make the proper automatic connections between the property instruments and the control mechanisms to satisfy complex relationships. However, there has been so much development of calculating machines and communication mechanisms for other purposes that we will probably find most of the basic elements and circuits available when they are needed.

Hydrodynamics of Pulp Suspensions

Another important field is hydrodynamics of pulp suspensions in water. From the time the wood chips are put into the digester until the paper is on the dryers, there is more water than fiber present, the amount of fiber running from about one-tenth of one percent to about six percent in various processes. Over this range the suspension properties change from those of a liquid to those of a plastic medium of a very special type. In this plastic form it is washed, bleached, beaten, mixed with dyes and sizing materials, cut, and pumped through pipes. It passes through this stage on the paper machine wire where the sheet is formed. In dilute suspensions containing from one-tenth to one percent of fiber the properties are essentially those of a liquid in which the fibers exhibit special behavior. The fibers are about 3 mm long and 3 hundredths of a millimeter in diameter. They have two outstanding characteristics in suspension, a tendency to concentrate into bunches, or flocks, and a tendency to become oriented in direction along the lines of flow whenever a velocity gradient exists. Both these tendencies are bad for the formation of a perfect sheet on the paper machine wire. The tendency of liquids to flow in a turbulent manner except when exacting conditions are fulfilled, is also bad for sheet formation. Look through any sheet of paper and you will see the effect of the flocks. Watch a square of paper curl when it is placed on a damp surface and you will see the effect of fiber orientation on the direction of curl. This direction is usually different according to which side is down. Another effect of fiber orientation often found is a peculiar galvanized appearance on the bottom side of the sheet when it is viewed in certain ways. The problem of forming a satisfactory sheet of paper on the wire is largely to overcome these difficulties at ever increasing speeds. Present speeds are from 200 to 1500 feet a minute, depending on the kind of paper.

A drawing of the wet end of a paper machine (Fig. 2) shows some of the means adopted. First the fiber stock is diluted to about one-half of 1 percent fiber and then passed through a vibrating screen. The design of an ideal screen is in itself an important problem. The screen serves two purposes; to remove dirt and fiber knots, and to break up the flocks. The stock then flows into a headbox running the full width of the machine and around one or more baffles the object of which is to remove the



(a) (b)

Sulfite pulp fibers 65×. *a*, in unbeaten stage, *b*, after beating.

The press part of a paper machine. The wet sheet is supported by a felt and water is squeezed out between rolls.

turbulence and stray currents arising earlier in the system. Actually with such a design only the violent turbulence is removed and some milder forms of turbulence are introduced. At the same time fiber flocks are forming again. Just before the lip of the headbox is placed a slowly rotating hollow cylindrical roll with large perforations in its walls, which has a mild action in breaking up fiber flocks and also in removing stray currents to attain an even distribution of stock across the lip. This roll brings in another type of turbulence due to the perforations. Here there is a typical dilemma. Violent action to break up fiber flocks creates turbulence, and allowing any appreciable region for smoothing the flow allows the formation of fiber flocks. The stock now issues onto the moving wire, at a head that will give it roughly the same velocity as the wire. The acceleration here, and any difference of velocity between wire and stock, both tend to give the fibers an orientation in the machine direction. To overcome this effect and also to help break up flocks, the whole wet end of the wire is shaken back and forth transversely as much as half an inch and two hundred and fifty times a minute. On very high speed machines this shake is not used because a high enough frequency cannot be attained. The shake introduces further fiber orientation effects particularly in the wire side layer of the sheet which is laid down immediately after the stock leaves the lip. Drainage of water is greatly expedited by a sucking action of the rolls that support the wire, and further down by vacuum boxes and a large suction roll. Near the lower end of the wire is a wire gauze roll that runs on the upper surface of the sheet and serves to smear out further the lumps caused by the fiber flocks. It is fairly apparent from the nature of these processes that the resulting sheet is apt to be two-sided in nature, in respect to fiber orientations, distribution of filler, size, dyes and fiber dimensions. Overcoming this two sidedness is a serious problem. Two-sided fiber orientation is one of the prime causes of curling in paper. Fibers expand and shrink differently in length and diameter with variations in moisture content, resulting in stresses in the two sides of the sheet which are relieved by curling. The prevention of curling is an annoying and often serious difficulty in the manufacture of paper. These problems of sheet formation and hydrodynamics of pulp suspensions constitute a large field for research and development.

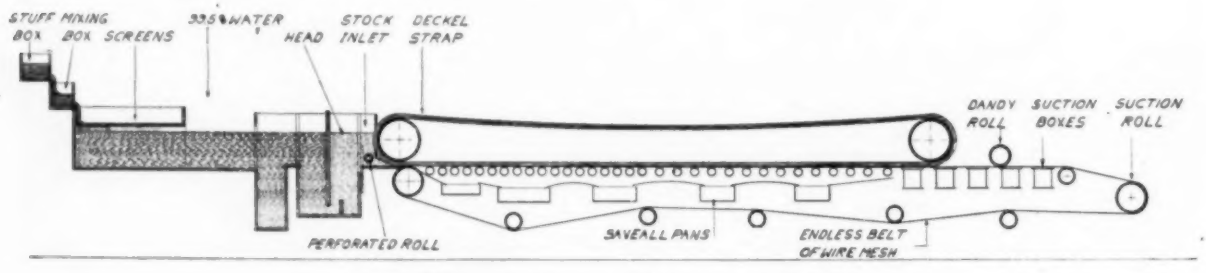


FIG. 2. Wet end of paper machine (or Fourdrinier).

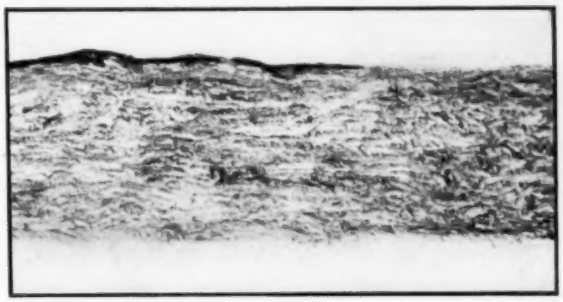
Physics of Surfaces

Another group of problems involves the physics of surfaces and this merges rather indefinitely into the physics of colloids. A sheet of paper contains a large internal surface in and around fibers and about half its volume is air space. A fiber itself is a hollow cylinder the walls of which are composed of several layers of fibrils wound spirally, alternate spirals in opposite directions. Whether the fibrils are bound together by some surface membrane of material other than cellulose is still a controversial question. The answer is important to the theory of beating where we are developing mechanically some surface property that makes the fibers stick together to form a strong sheet. Surface abrasion also affects the way in which dyes adhere to the fibers. The flocculation of fibers in suspension depends partly on surface energy relations. The technique of securing uniform penetration of wood by the cooking liquor depends on internal surface conditions, sizes of communicating passages in the wood, and the presence of air in the wood.

The fibers themselves exhibit very pronounced swelling and shrinkage properties and variations in rigidity with moisture content. The fibers are permeable to water vapor. The moisture content depends on the relative humidity of the air and also on the moisture history of the fibers. The phenomena belong in the region of surface and colloidal physics, and while a beginning has been made towards understanding them, there is still much to learn. Behavior of fibers with other liquids is very different to that with water.

Paper is sized with colloidal rosin precipitated onto the fibers with alum, to make it resistant to water penetration. Successful sizing is principally a matter of producing internal surfaces that are not readily wetted by water. The penetration of inks, satisfactory drying of inks, and prevention of ink spreading depend on attaining satisfactory surface properties on both internal and external surfaces of the sheet, as well as actual porosity of the sheet. The wide variety of inks and printing processes in use requires a wide variety of sheet characteristics in these respects, and there is much room for development of better methods of dealing with the problems involved.

Another serious surface problem is the accumulation of dirt on surfaces. Mineral fillers, dyes, fibers, pitch, and sizing materials tend to gather on surfaces and form masses of material which finally break off and appear as dirt in the paper unless they are constantly removed. It may be that much of this sort of difficulty could be eliminated by a study of the surface properties of the materials that are responsible for these accumulations. Surface properties may also conceivably be used to separate undesirable constituents, such as pitch which is a frequent source of dirt spots in the paper. Ore flotation is an outside example of such a process.



Cross section of offset paper showing penetration of printing ink. 250×.

Conclusion

In this paper I have tried to convey a picture of four classes of problems, problems in the efficiency of machines and processes, problems in automatic control, problems in hydrodynamics of pulp suspensions, and problems in the physics of surfaces and colloids. There are many others. I believe the conclusion must be evident that there is in the paper industry plenty of scope for the talent, knowledge and methods of the physicist, and that his work should contribute greatly to the progress of the industry.

The Physics of Subsidence and Ground Movement in Coal Mines*

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General Considerations

STUDIES of ground movement and subsidence in coal mines (and in other mines as well) involve the principles of mechanics and the properties of matter under stress. Coal exists in the ground in beds of varying thickness, extent, frequency and depth below the surface. Some beds lie essentially level and have suffered little disturbance beyond that caused by the weight of sediments deposited over them. Others have been involved in crustal movements which have tilted, folded, and sheared them with accompanying changes in the physical and chemical properties of the coals themselves. In the ground the coal is under stress from the weight of overlying material, and this weight plus that of the coal is transmitted to the next stratum below.

Removal of part of the coal immediately initiates redistribution of stress in all the strata involved. If enough coal is removed the stresses become greater than the strength of one or more of the strata, and mechanical failure is initiated. Underground such failures must be controlled to prevent injury to men or loss of equipment and working places. To do this requires use of artificial supports; these may be timbering of different kinds or backfilling of the open space with waste material; the backfilling may be partial or complete. In any case, the purpose is to reduce stresses in the strata so that dangerous breaks will not occur in the open areas in which work is being done.

The operator of a coal mine must also give consideration to the effect of his underground work on the surface above. Unless an excessive amount of coal is left in the ground unextracted, general subsidence of the surface is bound to occur over worked-out areas. If the surface is of little value and the operator has obtained release from damage claims, his concern is limited to such things as prevention of inrushes of water when mining is done under streams, and in general artificial supports underground need be of a local and temporary nature only. On the other hand, if the mine workings extend under built-up districts (as happens in many instances) great care must be taken to minimize surface movement and thus prevent damage to or complete destruction of improved property. In such cases it is necessary to use extensive artificial supports of a permanent nature, and backfilling is commonly employed.

For convenience one may use the term "structure" to designate the underground openings, the strata surrounding them, and the artificial supports used and then attempt an analysis of the stresses in the structure. For this work there is needed information on the mechanical properties of each member of the structure, the load on it, and the support given it by other members. Unfortunately, the mechanical properties of the strata involved are highly variable, as are also those of the artificial sup-

* Contribution from the Pittsburgh Experiment Station, U. S. Bureau of Mines, Pittsburgh, Pa. Published by permission of the Director, U. S. Bureau of Mines. (Not subject to copyright.) Presented at the Second Conference on Industrial Physics, University of Pittsburgh, May 22, 1937.

ports commonly used. Again one is largely concerned with behavior of the members in the range between the elastic limit and ultimate strength, with the further qualification that some members may be more nearly plastic than elastic bodies; as a result, time is a factor that cannot be neglected. Because of this many laboratory determinations of mechanical properties must be made simultaneously with quantitative observations of the behavior of typical structures formed during actual mining operations before a rational analysis of any one problem can be given.

Mechanical Properties of Coals

Technical literature contains many reports of mechanical tests of different coals made in laboratories. As an example, one may cite the work of Lawall and Holland[1] with coal from 11 beds in West Virginia. Compression tests were made of 3-inch cubes cut from larger blocks of coal. Stress-strain relations were curved lines with hysteresis loops of considerable size and measurable permanent set when load was released. Secant moduli of elasticity were computed on the basis of curves for ascending loads. These ranged from 370,000 to 615,000 for loads applied perpendicular to the bedding, and from 167,500 to 800,000 for loads parallel to the bedding. For the individual beds ratio of moduli perpendicular and parallel to the bedding planes ranged from 0.59 to 3.28. Crushing strengths in pounds per square inch ranged from 1682 to 4893 for loads applied perpendicular to the bedding, and from 1517 to 4208 for loads parallel to the bedding. For the individual beds ratio of crushing strengths perpendicular and parallel to the bedding ranged from 1.05 to 1.46.

Tests made by Rice and Enzian[2] show that extreme caution must be used in applying results of laboratory tests to conditions underground, particularly when the coal bed is traversed by a regular system of vertical joints or cleats with spacing considerably less than the thickness of the bed. For example, the Pittsburgh coal bed has two sets of these cleats, the first major and the second minor, approximately at right angles to each other. These cleats are frequently planes of discontinuity; tensile strength across them is always small and occasionally nonexistent. When large blocks are compressed these cleats open visibly, and failure results from disintegration along them. Rice and Enzian report average crushing strength of cubes of Pittsburgh coal, in pounds per square inch, as follows: six cubes 2.5 to 4 inches on a side, 2486; three cubes 10 to 12 inches on a side, 2008; one cube, roughly 30 inches on a side, 817; one cube, roughly 54 inches on a side, 306. Fig. 1 shows the relation of compression to load on the 30-inch cube. The scales on this graph are those of most use to the mining engineer. Fig. 2 is a close view of this cube compressed about 8 percent and shows how it failed by disintegration along the vertical joints

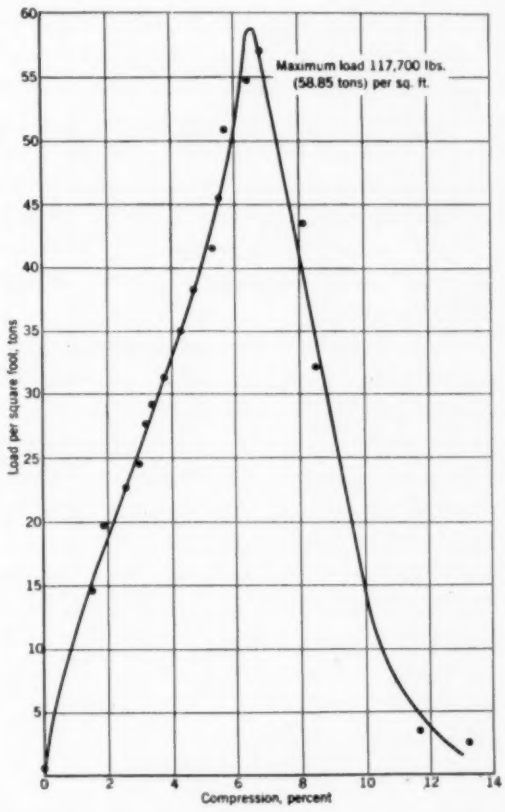

FIG. 1. Relation of compression to load on a 30-inch cube of Pittsburgh coal.

or cleats. In the mine this coal behaves in general as a brittle material of high compressibility but does not lose all supporting power instantly once failure is initiated.

It is obvious that the ratio of lateral dimension to height of a pillar of coal in a mine or of a

FIG. 2. Thirty-inch cube of Pittsburgh coal after failure, compression about 8 percent.

specimen in the laboratory will have an important influence on the strength thereof. In a mine this ratio will usually range from 3 to 10 for pillars that are to stand some time. During later extraction of such pillars, small blocks may be left standing with which this ratio is unity or less. Under some conditions these may be important supports of the overlying strata, and their sudden failure may initiate collapse of the strata immediately above.

To obtain data on the strength of coal that can be applied with confidence one must resort either to complicated test assemblies in the laboratory or to large-scale tests of the coal in place in mines. A few experiments along the latter line have been reported by Greenwald, Avins and Rice.[3] Underground it is far easier to make such tests horizontally (parallel to the bedding) than vertically, and the tests reported by these authors were made thus. Bearing strength decreased as area under compression increased. Mathematical extrapolation of the data indicated that the lateral bearing strength of the Pittsburgh coal bed might be in the neighborhood of 4000 pounds per square inch when large areas were involved. Extensions of this work and similar work in a vertical direction have been planned but as yet have not been carried far enough to permit making a report.

Mechanical Properties of Rocks Associated with Coals

Sedimentary rocks of all kinds are found associated with coal. The range of mechanical properties of these rocks is so great that limits set for the present discussion will permit mention of the two extremes only. At one extreme are the plastic materials, such as clays, which flow when a critical load has been exceeded. These are often met in coal mining, and fireclays of varying thickness immediately underlie many coal beds. When in the course of mining the load on pillars becomes greater than the critical value required to initiate movement, the underlying clay flows out into the adjacent passageways, and the floor of these passageways rises or "heaves." There are many cases on record in which this action completely closed the passageways, with resultant loss of the coal in the area involved. Knowledge of this plastic flow is confined almost entirely to qualitative observations by mining men, and a wide field of investigation is open at this point.

In extreme contrast to the plastic materials are the brittle, elastic rocks, such as hard sandstones and limestones, which are found as commonly as the plastic materials. Where these rocks are present immediately over coal beds and are thick and massive, their mechanical properties may be the determining factor in the movement of all the strata between the coal and the surface. There are cases on record in which methods of mining had to be changed to control such movement properly.

As an example of the properties of the harder brittle and elastic rocks one may cite data from tests of specimens prepared from samples of the Pittsburgh sandstone; these tests were made recently by the U. S. Bureau of Mines. In the locality where these samples were taken this sandstone is massive, approximately 50 feet thick, and its base is some 8 or 10 feet above the top of the Pittsburgh coal bed. Examination of this stratum along the edges of roof breaks in a mine revealed two distinct varieties. The first appeared to be a true sandstone with carbonaceous inclusions; the second had more the appearance of a very hard, finely-grained, dark shale. For convenience the two varieties were termed sandstone and shale. Chemical and petrographic analysis showed that the difference between the two varieties lay in the nature of the bond and the size of the particles bonded. The

sandstone consisted of quartz and mica grains, with an average size of 122 and 310 microns, respectively, held together with a silicate or silica bond. The shale also consisted of quartz and mica grains, but their size was only 6 to 7 microns and the bond was a carbonate. The content of carbonaceous matter was the same in the two varieties; in the sandstone it was segregated in discontinuous thin layers along the bedding planes, giving the rock a mottled appearance. In the shale it was finely divided and uniformly distributed, which resulted in a uniform dark gray to black color.

Cross bending tests were made of beams cut from the two varieties. First application of load produced some permanent set, but subsequent deflections were elastic in nature when the load was applied and released rapidly. When a load was maintained for some time additional permanent set was introduced. Fig. 3 illustrates the deflection load relation for three beams, two sandstone and one shale. Portions of the curves for ascending loads are straight lines, and an average modulus of elasticity of 3×10^6 was computed from these and other similar data for both the sandstone and shale. The average modulus of rupture was 2200 pounds per square inch for the sandstone and 990 pounds for the shale. When one applies these data to the condition of these rocks in the ground the effect of long-continued loading must be included, and deflections will always be greater than would be computed from a modulus of elasticity derived from a laboratory test of short duration.

Fig. 4 shows, from left to right, the two sandstone and the shale beams broken in cross bending, and in addition two sandstone cubes crushed, respectively, perpendicular and parallel to the bedding planes. The first cube failed at 19,400 pounds and the second at 14,000 pounds per square inch. Compression parallel to the bedding planes caused failure along them. Both the sandstone and the shale have low tensile strength across the bedding and are much weaker in shear parallel to the bedding than perpendicular thereto.

Extended work of this character has been done abroad. As an example, one may cite the work of D. W. Phillips.[4]

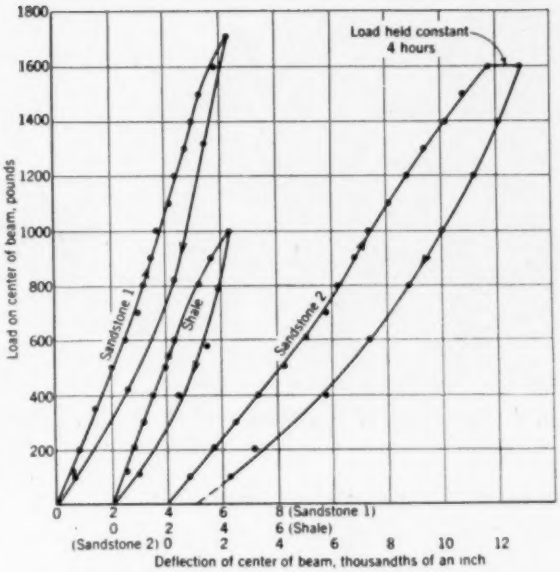

FIG. 3. Typical data from tests of rock beams.

Mechanical Properties of Artificial Supports

There have been many tests of the strength of artificial supports both in this country and abroad, and the extent to which studies have been carried in different countries is a fair measure of the relative importance of the problem to date therein. In this country, an excellent example of the necessity of providing support under improved surface property is found in the city of Scranton, Pa. It is estimated that before any mining was done the city area was underlain by 600,000,000 tons of anthracite contained in 11 separate beds ranging from 2 to 24 feet in thickness. By 1911 the amount of coal and waste rock removed totaled 198,000,000 cubic yards; this is somewhat greater than the excavation required for construction of the Panama Canal. Damage to surface property caused by subsidence resulting from this excavation had become so serious that the city employed two engineers, William Griffith and Eli T. Conner, to make a complete investigation with a view to prevention of further damage. Their report was published by the U. S. Bureau of Mines.[5] As a part of this investigation a number of tests of the bearing strength and compressibility of backfilling materials were made at Lehigh University; details are given in an appendix to the above-mentioned published report. Tests of supports of different kinds were continued by the Bureau

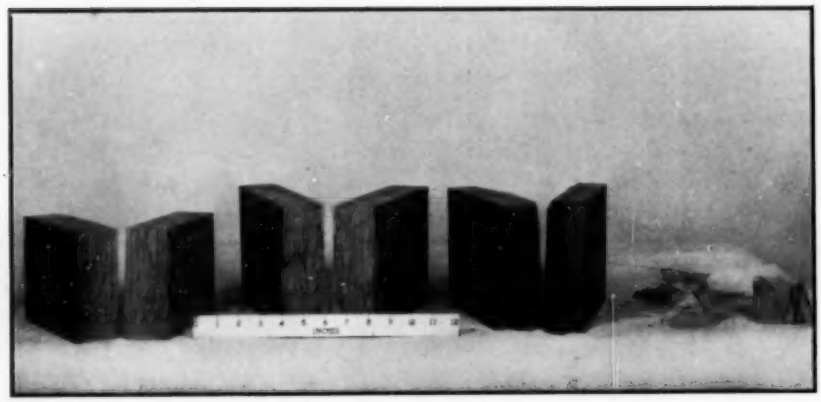

FIG. 4. Specimens of sandstone and shale after failure in cross bending and compression.

for the Pennsylvania State Anthracite Mine Cave Commission, and the data obtained were summarized in the publication referred to in reference 2. That paper gives full details and photographs of a number of tests.

The workings of bituminous-coal mines of western Pennsylvania have been and are mainly under unimproved surface, and problems of surface damage have been small compared with those encountered at Scranton. Because of the lower value of bituminous coal it is customary to leave blocks unmined when surface structures are to be protected rather than to resort to expensive backfilling. One problem of immediate importance in these mines has to do with temporary supports used in the vicinity of the working faces. Such supports are removed and the roof allowed to cave as successive, relatively small areas of the coal bed are extracted. Wood posts are commonly used for this purpose either with or without cross-bars directly against the roof. In some mines these are supplemented close to the line of break of the roof by cribs built of square-sawed timbers. When a break is to be made in the roof these cribs are taken out and subsequently re-erected at points farther from the break line, as may be required. The U. S. Bureau of Mines is now conducting tests of the mechanical properties of temporary supports as a part of its general program of study of the movement of roof in bituminous coal mines, but accumulated data are as yet too fragmentary to justify publication here.

British and German technical literature contains many papers describing large scale laboratory tests of artificial supports used in those countries. Because of the greater depth of the mines, more adverse geologic conditions in some cases, the more frequent necessity of protecting structures on the surface, and the widespread use of methods of mining which employ backfilling as an integral part of the work, such tests have been made in greater number in those countries than in the United States. For those who may wish to obtain further knowledge of the work done abroad a few references to British literature are given.[6]

Measurements of Strata Movement Underground

Systematic measurements of movement of different parts of the underground structure resulting from mining of coal have been conducted in England, Germany, and other European countries for some years past. More recently such work has been initiated in this country. There have also been many studies of the subsidence of surface in which measurements of movement underground were not made. A few typical references are included here, merely as examples of what has been done.[7]

Studies of movements underground were initiated by the U. S. Bureau of Mines somewhat less than two years ago, and it is expected that the first report will be published shortly. Measured movement is, of course, merely deformation of the portion of the structure on which the measurement is made, and the distribution of stress causing the deformation will usually be extremely complicated.

In general the mining of bituminous coal in western Pennsylvania can be divided into two phases: (1) advance work or development of the bed by driving passageways through it systematically so that the coal remaining is in fairly large blocks or pillars; and (2) retreat work or removal of these pillars as completely as possible, beginning at some boundary and working backward in the direction in which the recovered coal

is moved toward the mine opening. As a rule, both phases are in progress simultaneously in different areas of a given mine.

Advance work may remove 25 to 35 percent of the coal and with overburden no greater than that encountered in western Pennsylvania removal of this proportion of the original support does not cause sufficient concentration of stress in the overlying strata to necessitate any replacement of the support removed. An exception occurs when the material immediately overlying the bed is in the form of thin layers having little strength mechanically or when the layer first exposed disintegrates as a result of atmospheric action. Artificial support must be provided for these layers or else they must be removed. If artificial support is used during advance work its strength is determined by the weight of the immediate layers to be supported and not by the total weight of the overburden.

In general it may be said that one can measure compression of coal pillars during advance mining, but this compression and accompanying roof movements are too small to have any significance in so far as mining operations are concerned. For this reason studies of roof movement made by the Bureau have been confined to the second phase of mining mentioned above, namely, pillar extraction. Naturally, strata always move into any open space available; the roof moves downward, the floor upward, and the sides or ribs of the coal pillars outward. The relative values of these movements will depend on the mechanical properties of all the materials involved, on the manner in which they are loaded, and on the strength and frequency of artificial supports and the manner in which they are placed.

Measurement of these movements may be absolute or relative. Absolute measurements require reference to some base, the stability of which is assured, and such a base will of necessity be a considerable distance from the point of measurement. Surveying methods must then be used if one desires to ascertain the movement of all four walls of a passageway. If only vertical movements are desired, water leveling is possible when the necessary pipe or hose lines can be laid from the base to the point of measurement.

Relative movements are obtained more simply, as it is merely necessary to measure the reduction in distance between two points. This system is particularly applicable to measurement between roof and floor where the floor strata are such that their plastic flow is negligible or absent. For this work the Bureau uses the recorder shown in Fig. 5. This recorder consists of two telescoping tubes held in extended position by a strong spring. Attached to the outer tube is a bracket carrying a drum-type clock with chart; the inner tube carries a pencil or stylus. When placed between steel pins set in the roof and floor this instrument gives a time record of convergence of the strata in which the pins are fixed.

Fig. 6 is an example of the data obtained through use of the convergence recorder. In this case, conditions were such that movement was confined almost entirely to the roof. Records at this particular point covered 19 days, but movement of significance in connection with mining occurred only during the final 48 hours, and the record was terminated by a collapse of the immediate roof. Records such as this must be correlated with the progress of mining and the physical properties of the members of the structure in the immediate vicinity before quantitative conclusions are justified. In the case shown in Fig. 6 no coal was mined on Saturday and Sunday. The redistribution of stress under way at the close of work on Friday continued during the idle period and finally brought some of the immediate roof strata to the breaking point on Sunday morning.

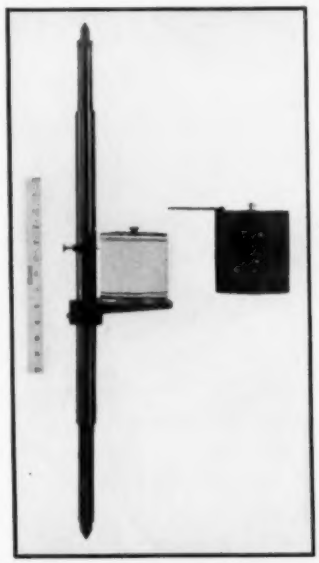

FIG. 5. Bureau of Mines convergence recorder.

When measurements are taken at a number of points surrounding a pillar of coal the general movement of the roof over the coal can be

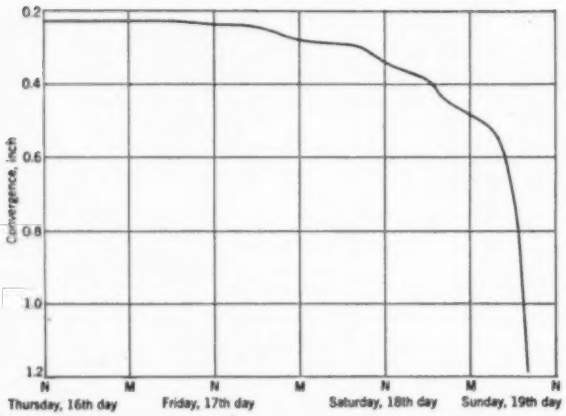

FIG. 6. Portion of a typical record obtained through use of convergence recorder.

followed. Fig. 7 is an isometric projection showing how the roof was warped over a portion of two pillars at one particular time during an investigation. Warping of the roof strata in this manner is found quite frequently.

When convergence records are obtained over a large area simultaneously contours of equal convergence can be plotted on a plan of the area, together with the extent of mining therein and, by use of appropriate symbols, the observed breaks in the roof. Comparison of such charts prepared at regular intervals is a valuable aid in understanding the behavior of the roof strata.

In work of this character it must be remembered that conditions are not static. Movement continues at many points after extraction of coal ceases, as Fig. 6 shows, and there is always a lag between the removal of support caused by mining a given block of coal and the ultimate effect of this removal. This is particularly true of subsidence of the surface. The rate of movement of the surface increases from zero to a maximum and then decreases toward zero, but many months elapse before the movement becomes so small as to be indistinguishable from the errors of measurement.

Theories of Stress Distribution in Undermined Strata

A number of investigators have advanced theories of stress distribution based on mathematical considerations, supported in some cases by laboratory tests of specimens or assemblies designed to simulate portions of structures formed underground by mining. A theory of arch stresses in the strata overlying deeper mine workings has received considerable mathematical discussion in the literature abroad.[8]

German literature contains reports of numerous laboratory tests of models designed to throw light on the question of stress distribution in and deformation of strata underground. In England theoretical considerations have been supported by photoelastic experiments on models.[9]

It appears to the writer that modifications or extensions of the various theories will be made from time to time during the next few years as additional information becomes available. Nor does it appear probable that any one of them will have universal application because of the wide range of conditions encountered. The arch theory is tenable without modification only where there are proper abutments on which the arch can rest. One abutment is on unmined coal in every instance, but the other must lie in an area from which coal has been removed. When this area has been closed by breakage of overlying strata it is sometimes observed that the fallen material is not in contact with the lower portion of the strata remaining unbroken.

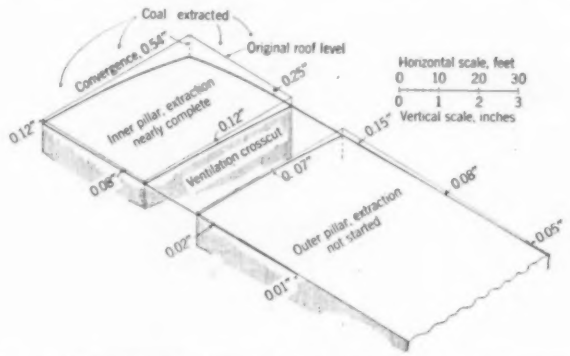

FIG. 7. Warping of mine roof over pillars projecting into an area from which coal has been removed.

Obviously the second abutment is missing in such a case, and the strata having no contact with fallen material should be considered as cantilevered plates. This does not preclude the presence of arch stresses in higher strata that have the necessary bearing on the fallen rock at some point. Consideration of strata subsiding over mine workings as bent plates has been given attention in Germany recently by Hermann, Stöcke, and Udluft.[10]

Experiments making use of photoelastic measurements on suitable models should be of much value in determining stress distribution in members of the complicated structures that result from mining. Additional work along this line is needed in the immediate future. Information thus obtained, coupled with proper knowledge of the mechanical properties of the materials which must support the stresses, should yield better solutions of problems of control of ground movement which the coal-mining industry faces continually.

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Beneath the immense variety of Nature's structures lie certain remarkable simplicities. Thus the elements used in the building are surprisingly few in number. There are but ninety-two in all, of which only a few are of common occurrence, and many are used very sparingly. Indeed there are one or two of which it can only be said that they should exist, though as yet they have not been found. Oxygen constitutes half of the known world, half the remainder is silicon; aluminum comes next. In living things carbon is one of the most important elements, yet it constitutes only a fraction of one percent of the world as a whole.—SIR WILLIAM BRAGG.

("Recent Crystallography," *Nature*, May 22, 1937)

Trilinear Coordinates

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TRILINEAR coordinates have been widely used to represent the properties of ternary alloys since 1881 when Thurston[1] first published several sets of contour curves giving the properties of copper-zinc-tin alloys. Later Gibbs,[2] Stokes,[3] and Roozeboom[4] applied trilinear coordinates to the study of various ternary chemical compounds. However, in all these cases the coordinate system used was based on an equilateral triangle. Trilinear coordinates are considered rather extensively in *Le Calcul Simplifié* by Maurice d'Ocagne, and also in *Traité de Nomographie* by the same author.[5, 6]

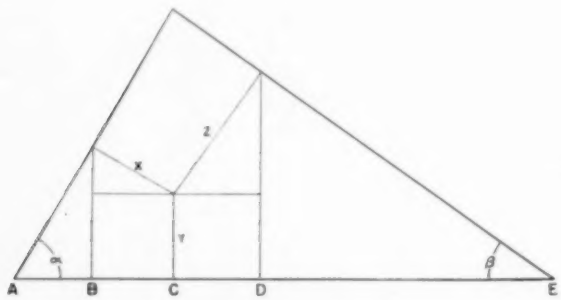

FIG. 1.

It is the purpose of this article to discuss the coordinate systems derivable from triangles in general, and multiple logarithmic scale charts, which are but a special case. Finally, as an example, a multiple logarithmic chart will be applied to the representation of magnetization-permeability curves.

Consider the triangle shown in Fig. 1, and defined by the side AE and the angles α and β. Then:

$$\begin{aligned} BC &= x \sin \alpha, \\ CD &= z \sin \beta, \\ AB &= (x \cos \alpha + y) \cot \alpha, \\ DE &= (z \cos \beta + y) \cot \beta, \\ AE &= AB + BC + CD + DE = S. \end{aligned} \tag{1}$$

Hence

$$x \sin \beta + y \sin (\alpha+\beta) + z \sin \alpha = S \sin \alpha \sin \beta. \tag{2}$$

In the event $\alpha = \beta = 60°$,

$$x + y + z = (\sqrt{3}/2)S. \tag{3}$$

Eq. (3) expresses the fundamental property of the equilateral trilinear coordinate system, and clearly shows that whenever three variables are so related that their sum is a constant, all three may be represented by a single point in the coordinate plane.

It is this fact which has made the system applicable to the representation of ternary alloys. For if x, y, and z represent the fractional parts of elements X, Y, and Z entering into an alloy, every point in the x, y, z plane represents a possible composition, and any property of the composition may be represented by properly drawn contours.

Equilateral coordinates may also be used for the representation of products; for consider the quantities X, Y, and Z related such that

$$XYZ = A, \tag{4}$$

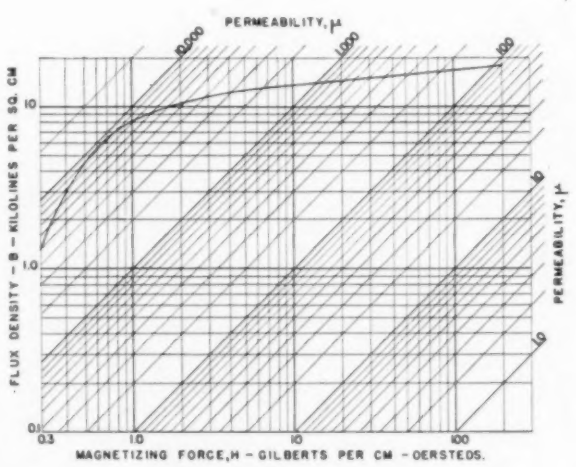

FIG. 2.

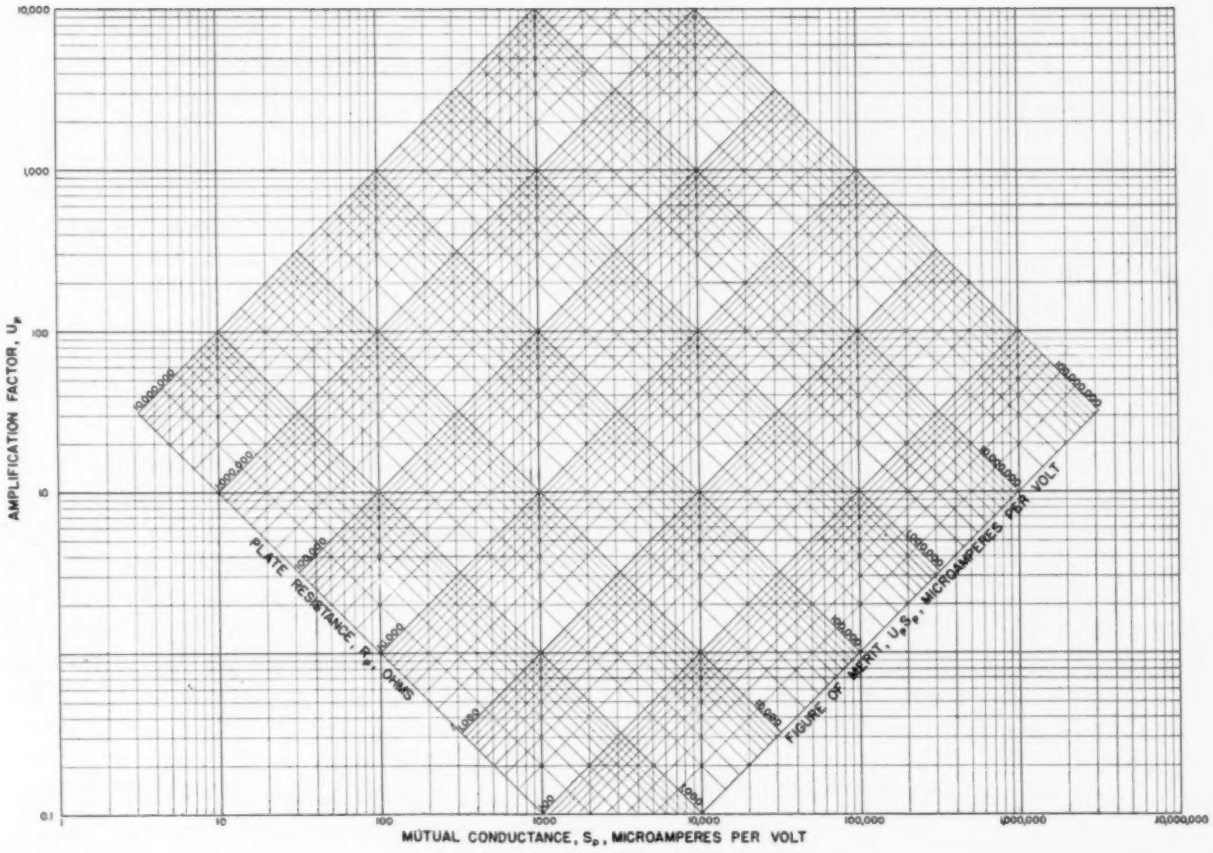
AMPLIFICATION FACTOR, U_p
PLATE RESISTANCE, R_p, OHMS
FIGURE OF MERIT, $U_p S_p$, MICROAMPERES PER VOLT
MUTUAL CONDUCTANCE, S_p, MICROAMPERES PER VOLT

FIG. 3. Tube classification chart.

where A is a constant. Then

$$\log X+\log Y+\log Z=\log A, \tag{5}$$

and since (5) is of the same form as (3), it is apparent that any set of possible values of X, Y, and Z can be represented by a single point in the coordinate plane provided only that logarithmic ruling be used. This type of plot has been used by the author as a possible basis of classification of thermionic vacuum tubes.[7]

As an example of the use of more general trilinear coordinates, consider the system of equations

$$\begin{aligned} x+ay+bz&=c,\\ \Phi(x, y)&=0, \end{aligned} \tag{6}$$

where a, b, and c are constants, and let it be required to find that coordinate system in which all values of x, y, and z may be represented by the same scale. Eq. (2) may be written

$$x+\frac{\sin(\alpha+\beta)}{\sin\beta}y+\frac{\sin\alpha}{\sin\beta}z=S\sin\alpha. \tag{7}$$

Comparing (6) and (7) it is clear that the desired coordinate system is defined by the relations

$$\begin{aligned} \sin(\alpha+\beta)&=a\sin\beta,\\ \sin\alpha&=b\sin\beta,\\ S\sin\alpha&=c. \end{aligned} \tag{8}$$

The first two equations of (8) may be used to determine β such that

$$\cos\beta=(a^2+b^2-1)/2ab, \tag{9}$$

from which α and S follow at once. Then on plotting the curve $\Phi(x, y)=0$, all values of x, y, and z consistent with the requirements are at once determined. Examples of this type of computation are frequently met with in physics and engineering, particularly in connection with heat and energy balances, etc.

Similar methods will give a plot of

$$X^nY^mZ^p=A, \tag{10}$$

where it is desired that all the variables have the same scales (or scales differing by some factor),

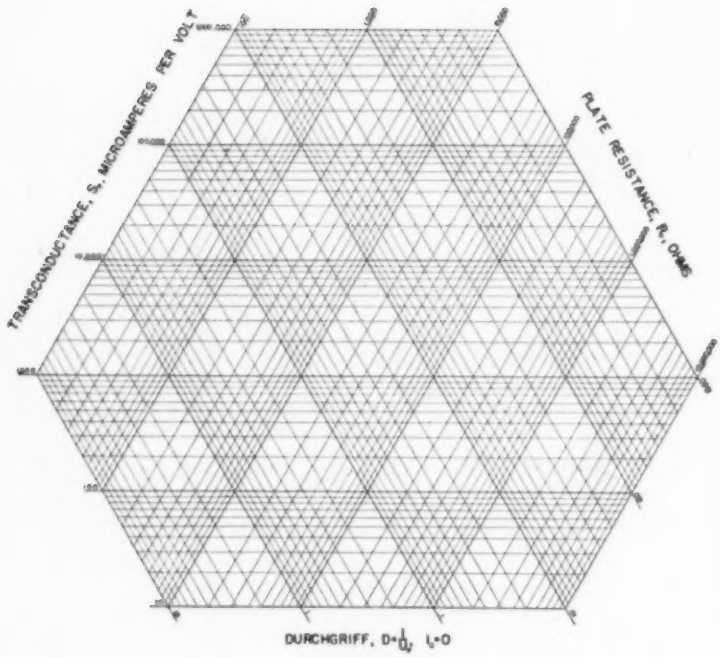

FIG. 4. Tube classification chart.

for then

$$\log X+(m/n)\log Y+(p/n)\log Z=\log A, \quad (11)$$

and the coefficients of this expression may be compared with Eq. (7) in order to determine the basic triangle.

There is a large class of three-variable problems in which the relation between two of the variables is of greater interest than the relation between either of those variables and the third. In all such problems it is desirable to retain two of the coordinate axes at right angles as in ordinary Cartesian coordinates, and to permit the third to assume such an angle as may be dictated by the choice of scales, etc. Thus, if $\alpha=\pi/2$, Eq. (2) takes the form:

$$x+y\cot\beta+z\csc\beta=S. \quad (12)$$

Eq. (12) clearly shows that the trilinear relation will be preserved, but that there is a restriction on the coefficients of y and z imposed by the functions of the angle β. However, any equation such as the first of Eqs. (6) can be plotted in any coordinate system by proper choice of scales.

As an example of the applications of Eq. (12), consider the relation between flux density, B, magnetic intensity, H, and permeability μ,

$$B=\mu H. \quad (13)$$

It is customary to plot B, H curves and μ, B curves on the same sheet in ordinary rectangular coordinates. Two curves are required and cross reference between these curves is necessary to obtain the values of all three variables.

To design a trilinear coordinate system for this equation, and at the same time maintain the B and H axes at right angles, write

$$10\mu H/B=10, \quad (14)$$

$$\log 10H-\log B+\log\mu=1. \quad (15)$$

The quantity $10H$ may be used in making the plot, but the scales may be labeled so as to make the plot direct reading. Comparing (15) and (12) it is clear that the appropriate value of the angle β is $-45°$, provided that the scale of $\log\mu$ is smaller than the scales of $\log B$ and $\log H$ by the factor $1/\csc\beta=1/\sqrt{2}$. Multiple logarithmic scale coordinate paper such as that here indicated has found a variety of uses in physical and engineering problems, as, for instance, in the vacuum tube classification charts of Zilitinkewitsch,[8] Mimno,[9] and others,[10] and in the reactance-resonant frequency chart of Slonczewski.[11]

A B, H, μ curve is plotted in Fig. 2, and it is believed that an inspection of the plot will show that it greatly facilitates magnetic circuit computations. Charts which are particularly useful in vacuum tube classification are shown in Figs. 3 and 4.

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Physics of Air Hygiene*

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HYGIENICALLY pure air to breathe is at least as important to man as are pure water and pure food. For various reasons, the public has not been as insistent about the first as it has been about the latter two.

With the concentration of population into larger and still larger communities, and with the increase in volume and variety of industrial activities, city atmospheres have become laden with smoke, dusts and gases that, to say the least, are obnoxious, and some of which are responsible for definite harm.

In 1924, Gibbs[1] gave the general name *aerosol* to the disperse systems in air, such as dust, fumes, smoke, etc. Drinker and Hatch[2] present an excellent brief discussion of the properties of dust, fumes and mists.

Dust results from reducing earthy materials to small size; fumes from processes such as combustion, sublimation, and condensation; smoke from combustion; mists or fogs by condensation of water vapor upon nuclei, or by the atomization of liquids.

Air pollutants may also be classified according to whether they immediately enter the city atmosphere, or whether the concentration is in industrial plants.

Urban air pollution includes all contaminants that are in the city's atmosphere; most of them are products of combustion of fuel and of such industrial processes as exhaust dusts and gases directly to the outside.

Industrial air pollution consists of those impurities, such as dusts, fumes, etc., which are freed in the plant and to which workmen may be exposed. Obviously, here the possibilities of dangerous concentrations are greater than in outside air.

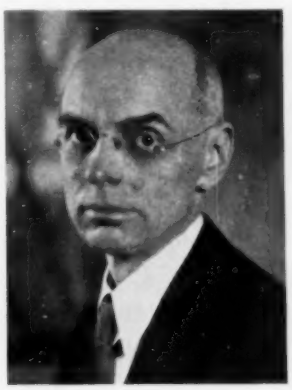
In both cases, the size range of solid particles is from those large enough to drop out immediately to those so small that they will remain in suspension indefinitely.

Atmospheric Contaminants

As has been said, these consist mostly of products of combustion—smoke, cinder, fly ash, and sulfur and other gases. Smoke (tar and carbon particles) results from incomplete combustion; cinder is a mixture of unburned or partly burned fuel and ash; fly ash is emitted in proportion to the velocity of the gases and the absence of separation; and sulfur compounds are in proportion to the amount of sulfur in the fuel as fired.

As these products of combustion enter the atmosphere, there begins at once a process of settling of the solids and diffusion of the gases. The extremely fine particles of carbon that make up the visible smoke gradually disperse; soot and cinder largely settle out and are responsi-

H. B. Meller



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ble for most of the aggravating nuisance in and around the homes; the ash, highly siliceous, falls or remains in suspension, according to the particle size and shape. The tar acts as so much black paint would do, and in addition, occludes sulfur acids, making possible through contact with building material or fabrics complete action by the acids so occluded.

Field of the Bausch and Lomb dust counter showing how easily dust counts can be made.

Smoke and dust in the air aid in the formation and prolongation of fogs, and increase their density, by supplying additional nuclei for condensation of water vapor, by increasing the concentration of smoke particles in the absence of wind of a velocity sufficient to move the particles as rapidly as they are emitted, and by retarding or preventing penetration of sunlight to evaporate the water.

The amount of sunlight in a smoky city is measurably less than in a cleaner city. This depletion of light is, naturally, more marked in the shorter rays—the blue, violet and ultraviolet—than in the longer ones—the red and infrared.

The concentration of solid particles in the atmosphere varies inversely with the wind velocity—the lower the wind velocity, the less rapid the dispersion—and during the heating season it varies inversely with the temperature—the lower the temperature the more fuel burned for heating and the greater the amount of pollution entering the atmosphere.

The effects upon community health are not so clearly shown. Products of combustion entering the upper respiratory tract of the individual have a definitely irritating effect. It has been claimed that disorders are aggravated or caused in the nose, throat and lungs. It seems to be a fact that there is a higher percentage of nose and throat specialists in a smoky city.

Industrial Dusts

These come from some of the raw materials used in industry, as well as resulting from industrial processes. The handling of raw materials, such as sand, may produce dangerous concentrations. Processes like crushing, grinding, drilling, produce dust particles in sizes ranging from the easily visible to the submicroscopic. If not removed at the source, the dust is in the air which the workmen breathe. Over a period of time, a sufficient quantity of the fine particles may accumulate in the lungs to cause a definite occupational disease called pneumoconiosis. The engineer has developed effective methods for determining whether a dust concentration is hazardous, and in most instances for controlling it at the source. Where this is not possible, there are masks and respirators which men may wear so that they may work in safety.

While of course the danger from hazardous dusts is in the plant where they originate, more or less gets into the outside atmosphere, adding to the pollution there.

Determination of Impurities

In dealing with the problem of eliminating atmospheric impurities, it is necessary to determine what the impurities are, how much of each is present in a given volume, and how much of each is sufficient to cause damage to human beings, to animals or to vegetation. When the contaminant is a dispersed solid or liquid, the methods of estimating its concentration are mostly physical, involving either fixing the dispersoid in a position where the particles may be examined and counted under the microscope, or estimating it by opacity measurements while still in suspension.

One of the methods of collecting solid particles is by filtration. In the successful processes of this type, the filter consists of a soluble or volatile

substance. Sugar is frequently used, and salicylic acid has been used experimentally as a volatile filter. Filtration is especially useful if the collected material is to be weighed. However, the number and size of particles are of more consequence than their weight, because the larger particles, especially those over 10 microns, which most influence the weight, are of little importance hygienically, because they do not enter the lung cells, and because the surface area of the particles is a greater factor in their absorbability in the tissues than their bulk. Although the collected material may be obtained in a countable form, small quantities of impurities in the filtering material may be sufficient to nullify the accuracy of the count.

A second method is to collect the insoluble impurities in a liquid, usually water, and to count the particles in a known fraction of the volume. The Greenburg-Smith impinger is the instrument most generally used in the United States, and has a quasi-legal status because it has been used to determine the safety limits for silica dust. A known volume of air is drawn through a sufficient quantity of liquid, which is then made up to a definite volume, and 1 milliliter is placed in a specially constructed cell, portions of which may be counted with the aid of ruled squares in the eyepiece of the microscope.

A low magnification, i.e., 100 diameters, must be used with the impinger, on account of the necessary distance between the sample and the objective. However, particles as small as 1 micron are visible. Dark field illumination, revealing smaller particles, is in growing use with this method.

In a number of instruments the dust is impinged on a practically dry surface. This type makes use of the inertia of the particles by which they continue moving in a straight line and are deposited through an orifice on a glass surface while the air is quickly drawn away at an angle. In instruments such as the Hill counter and the konimeter, adhesion to the glass is secured by the use of an oily film; in the Owens and Bausch and Lomb counters, the air is first saturated with water vapor, the condensation on expansion wetting the particles so that they adhere for sufficiently long periods. In some of these instruments the collecting disk is a thin cover glass and the deposit may be examined under oil immersion on the reverse side of the disk. Thus particles down to 0.2 or 0.3 micron are visible under light field magnification; dark field illumination also is applicable. The most recently developed instrument of this type is the Bausch and Lomb counter, in which the sampler and microscope are combined in compact form. Moderate dark field illumination at 200 diameters is used. All of these instruments are useful for atmospheric as well as industrial dust.

Electrostatic precipitation is utilized for sampling in an instrument such as that developed by the Westinghouse company and another in use at the Bureau of Mines. Electrons liberated from a highly charged wire charge the dust particles, which are then collected on the opposite pole. One side of the container has a recess for a microscope slide; this receives its proportionate share of the total dust, which may be counted thereon.

An Owens jet dust counter.

The thermal precipitator makes use of the principle of the dust-free space surrounding a hot body. The air is drawn through a narrow space bounded by two cover slips, between which passes a heated wire. The dust is de-

A Bausch and Lomb dust counter.

posited in a narrow strip on each of the slips and is counted as in the other methods.

Finally there are the optical methods, by which the dust is not deposited but the opacity of the air is measured. One branch of a divided beam of light passes through the dusty air, and the other through clean air with an adjustable shutter or other interfering device, so that adjacent visual fields may be compared directly. Balanced photoelectric cells also may be used, changes in opacity of the air samples being indicated by changes in current developed. Ultraviolet light is also used with suitable photoelectric cells and electrical means of comparison, as in the instruments used for measuring transparency of the atmosphere. All optical methods must be calibrated by actual counting methods for the particular nature and fineness of dust.

In recording instruments, the filtering and optical methods are used. In the Owens recorder a constant stream of air is drawn through a moving ribbon of filter paper. The density of the deposit may be observed directly or more accurately by a photoelectric cell actuating a moving pen. In the optical recorders the setup is the same as mentioned previously, except for the addition of a recording potentiometer.

All these methods give the total quantity of dust per unit volume, without reference to its composition. When an analysis is desirable, the impinger or some other tests may be prolonged sufficiently to give a large enough sample for chemical analysis. For some purposes, however, a chemical analysis is insufficient; for instance, free silica, the prime factor in the causation of silicosis, is determined chemically with great difficulty. Petrographic methods are applicable in such cases. The polarizing microscope is not very useful in this connection, because the particles of greatest interest, those under 5 microns, do not show the interference colors well enough to be recognized. The immersion method, however, is generally of value. The sample is immersed in oils of known refractive indices, and the behavior of the Becke lines in each oil is used to establish the percentage of particles between each pair of refractive indices. This method is limited in application, because the finest particles require a considerable difference in refractive index between them and the liquid in order to be seen.

When the contaminant is a gas or a soluble substance dissolved in dispersed water, the method employed is to pass it through a suitable absorbent and determine it by chemical methods. In many cases the gas or spray is passed through an impinger or a similar instrument and the concentration determined chemically or electrometrically. Rapid and simple methods have been developed for carbon monoxide, sulfur dioxide, mercury, benzene and other organic liquids, and carbon monoxide recorders are available commercially.

Time does not permit discussion of the various methods of determining dust and other impurities. It is sufficient to say that there is no perfect instrument, and probably will not be, that is applicable under all conditions and for all types of dust. It is possible, however, that improvements in the present forms of apparatus will lead to types well adapted for individual problems.

Control of Impurities

We must pass on to the more general problems of control of impurities. Practically all atmospheric contamination is man-made, not excepting dust storms, and the ideal place for its elimination is at its source. With the exception of dust storms, the factories must be the seat of efforts in prevention of pollution. Smoke, which constitutes the greatest proportion of urban atmospheric pollution, can be prevented largely by proper choice of fuel and design of boilers and furnaces so as to insure complete combustion. For residual smoke and other materials that may escape from factories, the methods applied are filtration, washing, centrifugal action and electrical precipitation.

Filtration is more readily applicable to relatively light quantities of dust, and as used in air conditioning is employed most extensively in rooms where the dust is raised or the outside dust is to be kept out. Moreover, it is often inefficient for some of the particles that it is most desirable to eliminate, for instance free carbon particles and fine silica. Filtering materials include fabrics, cotton, and glass wool, which may be impregnated with oily substances. In commercial filtration, the air often is passed through a number of bags which afford a large collecting area.

Washing methods are used in connection with air conditioning and in factory stacks, especially with gases and other soluble impurities. The general method is to pass the exhaust gases through a scrubbing tower. Dust may be separated by this method also. In one form of equipment, a frothing agent is added to water, and the principle of flotation is used in collecting the dust.

There are several types of cyclone separators, which consist of fans in the path of the dust, forcing the dust at right angles to the air flow by centrifugal action. In this method collection and removal of the deposited dust are simplified.

The electrical precipitation principle has been employed for many years in the Cottrell process. The charging wire consists of a chain suspended in the stack, and the collecting areas are baffle plates which may be removed for cleaning.

All these methods have been recommended from the viewpoint of general health, but the economy factor is important. There are many cases in which a manufacturer has been compelled to install dust removal equipment and has found that it paid him in dollars and cents, many times its cost.

Air pollution in factories does not affect as large a proportion of the population as does atmospheric pollution, but the consequences of long exposures to high concentrations are often more severe. Important examples are silicosis, asbestosis and other diseases resulting from the inhalation of dust; others are poisoning by lead and by organic solvents. The only remedy for silicosis and similar diseases is dust prevention. A good general exhaust system, preferably with one of the methods used for removing impurities, will in most cases control the hazard. However, the dust raised in particular locations is often insufficiently removed by such systems, and exhaust hoods or other appliances adapted to the particular process are necessary. The design of such exhaust hoods is a physical and engineering problem on which much has been accomplished but much remains to be done.

A typical dust respirator.

A typical respirator for poisonous gases and vapors.

Drilling in mines and excavations presents an intensified problem. One general method is wet drilling, of which one form consists in the use of a spray. Although effective in many cases, in other instances the spray method is open to controversy. In wet drilling processes, not involving spray, the water is supplied from a jacket outside the drill.

In dry drilling an exhaust system may be applied near the point of the drill, so that the device is most effective where the dust concentration is highest.

In addition to the use of exhaust systems, general good housekeeping is of assistance, including frequent cleaning of places where dust may develop. The laying of dust in mines by wetting agents should be mentioned in this connection.

As a last resort, when other methods fail, are not applicable, or have not been put in use, the worker may be protected by the use of a respirator. A dust respirator consists essentially of a filter for inhaled air without too much resistance to breathing, and is provided with a suitable bypass for the exhaled air. For the past two years the Bureau of Mines has been testing respirators and certifying approval of thos passing the tests.

Sandblasting presents a particular problem on account of the high concentration of silica in the air. In all modern factories sandblasting of large objects is carried on in an enclosed room and the operator is equipped with a positive pressure helmet, which fits over the head and shoulders and is attached to a supply of fresh air.

This is a very brief resume of preventive methods, most of which, as will be obvious, are based on the laws of physics.

Future of Smoke and Dust Abatement

For fuel-burning plants, we may look for further (material) improvement in boilers and furnaces, automatic fuel feed, dust separators, and for a feasible method for sulfur. We shall also see a rapidly increasing use of processed fuel, especially of coke for the small user. In many of the larger cities there is now agitation for much more stringent regulation. New legislation in some of these cases may be expected in the near future. National technical societies have committees working on the problems of practical standards and feasible ordinances. The solution lies in prevention; protection, except indoors through air conditioning, is not possible once the pollutants are released. Looking forward, is it too Utopian to think of a time when decreasing generation and distribution costs will make possible the use of electricity for all heating and power demands?

In the industries, many laws in many states attempt to provide for control measures to protect workmen against dangerous concentrations of hazardous dusts, fumes and gases. A lot more fundamental research is necessary before the desired prescription can be written. Engineering (in prevention) is ahead of medicine (in action and effects of the pollutants). Control of these dangerous by-products of industry lies in preventing their mixing with the air which is breathed by workmen.

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Impregnation Studies with Colloidal Graphite

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AMONG the processing techniques employed by industry to effect greater utility from common substances, none is more important than the art of impregnating solids with liquids. Materials like cloth, felt, leather, asbestos, paper, wood and metal, when coated or impregnated by appropriate vehicles, are given such characteristics as coloring, durability, lubricity, conductivity and opacity.

Among the impregnating liquids available for this purpose, finely divided solids in suspension are particularly useful. Of such dispersions, colloidal graphite, by reason of its purity, particle size, inertness, lubricating and conductive properties, is a typical impregnant. Briefly, the tendency of such dispersions to wet a solid and to penetrate its pores is no different from that of a liquid. In fact, the fluid is the carrier of graphite and after it has once penetrated into the pores, certain processes occur that cause the graphite to deposit within the capillaries of the solid.

The two most important factors connected with impregnation are the degree of wetting of the solid by a liquid (i.e., the adhesion tension of the fluid against the body) and the magnitude of the solution's surface tension. The work done when a "dry" solid is completely immersed in a given liquid, is designated as work of immersion, Wi, while the actual change is represented by

$$Wi = S_1 - S_{12} = \Delta F = A_{12} \qquad (1)$$

and can be determined by measuring the surface tension of the liquid and its angle of contact while existing as a drop on the solid's surface. Young's[1] expression for this condition is

$$S_1 - S_{12} = S_2 \cos\theta. \qquad (2)$$

When a liquid spreads over the surface of a solid the energy changes involved are somewhat different from those that occur while immersing solids in liquids as a new surface is formed. Work of spreading, Ws, per unit area is given by

$$Ws = S_1 - S_{12} - S_2 = S_2(\cos\theta - 1); \qquad (3)$$

whence it follows the conditions most favorable to the spreading of a liquid over a solid are:

(1) High surface tension of solid, S_1;
(2) Low interfacial tension of liquid against solid, S_{12};
(3) Low surface tension of liquid, S_2.

From Gibbs'[2] formulation on adsorption relating to impregnation techniques:

$$w = \frac{-c}{RT} \cdot \frac{dS_{12}}{dc}, \qquad (4)$$

dS_{12}/dc must be negative in order to obtain positive effects; that is, the interfacial tension between solid and liquid, S_{12}, must decrease, preferably from an initially high value. Maximum adsorption, then, would occur from a liquid that will give a low degree of wetting against the solid. At the same time, the liquid should not possess too high a degree of attraction for the material that is to be adsorbed from it. Moreover, the substance that is to be adsorbed should possess a marked affinity for the solid upon which adsorption occurs. In general, one might not arrive at optimum penetration but might still obtain complete adsorption with a given system. Wetting agents improve penetration without decreasing the amount of adsorption.

Likewise, the surface properties of the material to be impregnated (i.e., its wetting characteristics) are of importance in determining the degree of wetting.

Finally, the Fichtner-Sahlbom[3] effect from surface charges affects impregnation. If the solid to be impregnated is of electrical sign opposite to that of the colloidal graphite particles in the impregnating medium, the particles will flocculate on the outer portion of the solid body and will be adsorbed and held to some extent on these outer surfaces. Particles so adsorbed may tend to clog the pores, serve as ultrafilters, and, consequently, prevent penetration of additional graphite.

Consider, now, the treatment of commercial products, like cloth, paper, asbestos, leather, wood, cork, and porous materials, whose utility is increased by imparting thereto qualities of lubricity, conductivity, and coloring.

The impregnation of unsized, light-weight cloth is accomplished simply by immersing the fabric in unheated, agglomerate-free dispersions of graphite, prolonged immersion in warmed solutions being at times helpful. On the other hand, heavy-weight cotton ducks, belting stock, and felts, that frequently are one-fourth of an inch or more in thickness, are sometimes difficult to impregnate thoroughly. This result can be attributed to (*a*) an electrical charge on the surface of the stock causing neutralization and adsorption at the outer portion of the fabric, (*b*) presence of moisture that discourages capillarity, (*c*) existence of occluded air within the specimens, and (*d*) prior use of weighting substances that act as ultrafilters. Fortunately, heat treatment of the stock in question will eliminate each of the above obstacles prior to impregnation with solutions like colloidal graphite. Weighting materials are removed by boiling. While low temperatures applied directly to the cloth will dissipate the electrical charges, higher heat treatment for prolonged periods of time are usually required to exclude moisture and air.

It is interesting to note that graphited cloth approximates the constituents of natural soiling, with the result that research and control laboratories associated with the laundering industry use such specimens as comparative soiling standards,[4] the brightness values thereof being measured by an optical system[5] including a Martens photometer.

Paper stock, whether of the tissue grade used in electrolytic condensers or of the heavier type useful in automatic recording and duplicating machines, is impregnated readily by passing the same through agglomerate-free baths of aqueous colloidal graphite. Changes in dilution, obviously, alter the electrical characteristics of the treated paper, a wide range of conductivity values being, therefore, possible. Colloidal graphite may also be added directly to the beater during the manufacture of the paper to produce homogeneous results. In this case electrolytes like zinc chloride or aluminum sulphate are subsequently added to the mix for the purpose of affixing the graphite to the pulp fibers.

The impregnation of asbestos fibers is best achieved when colloidal graphite is added to the pulp masticators as in the case of paper. For the production of asbestos felts used in brake linings, the fiber is agitated in aqueous colloidal graphite until the latter constituent is absorbed. About one ounce of fiber is mixed with each gallon of water during this process, so as to obtain an even dispersion of the fibers throughout the water. The water and fiber, in constant agitation, are now fed evenly onto a sheet of fine brass mesh; then the water passes through, leaving it covered with a layer of asbestos fibers. Another sheet of mesh is now placed on top of the fibers and the two sheets with the fibers between are passed through rollers to remove the water and to consolidate the fibers into a sheet of felt. If a thick felt is desired, the thin sheets can be combined, or a second layer of fibers formed on the first and the two pieces of mesh again passed through the rollers. By repeating the procedure a thick sheet of felt can be obtained which is dense and well bound together.

The density of leather, its gelatinous nature, and the presence of various chemicals used in its tanning, are factors contributing to only partial impregnation when treatment is attempted through the interior side. Greater assimilation is obtained, however, through the pores or exterior of the hides. An alternative process, having possibilities in special applications, consists of finely perforating the leather and filling the openings with concentrated forms of colloidal graphite.

Lignous substances like wood may be impregnated by simple soaking or saturation. They are best treated, however, by centrifugal pressure devices. Frequently, in the production of friction

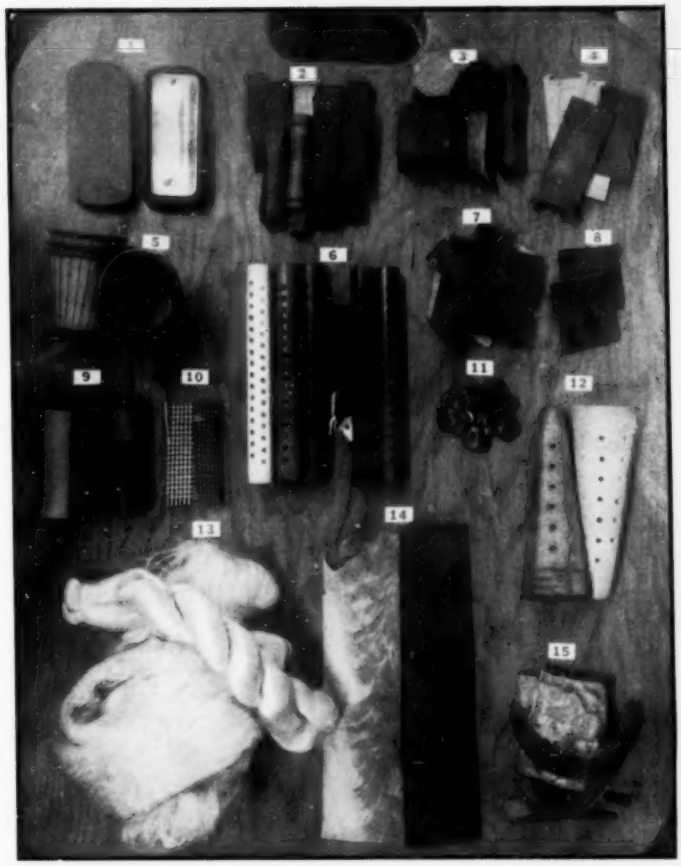

FIG. 1. Wood, paper, and textile items impregnated by centrifugal means. See descriptions below:

1. Black walnut brush backs.
2. Various woods impregnated by clear varnishes.
3. Various woods treated with Montan wax.
4. Transformer spacers.
5. Paper cups impregnated in stacks, 50 high, with Bakelite.
6. Perforated kraft-paper tubes.
7. Masonite, impregnated with viscous varnish.
8. Formed and unformed leather disks.
9. Spirally-wound cardboard tubes.
10. Paper threads treated with varnish to imitate Panama hat material.
11. Paper buttons impregnated to withstand hot water and machine ironing.
12. Paper cones impregnated with carbon tetrachloride-paraffin solution.
13. Specimens of "silk-soaking" by centrifugal means.
14. Experimental demonstration of walnut staining.
15. Paper pulp board.

elements from wood, synthetic resins mixed with colloidal graphite are either injected into the solid, or the wood is powdered and the mixture compressed under heat to form self-lubricating parts.[6]

Porous materials like grinding wheels composed of silicon carbide, aloxite, and alundum, bonded by suitable agents, may be immersed, under reduced pressure, in a suspension of finely divided graphite in water containing a small portion of dextrine, the latter substance acting as a temporary binder for the graphite after the subsequent removal of the wheel.[7] Wheels so impregnated with colloidal graphite yield greater abrading efficiency, for the graphite acting as a dry lubricant decreases the frictional losses. Finally, in those instances where the grinding action is electrically controlled, colloidal graphite is also incorporated in the porous minerals to render the wheel conductive.

Apart from the direct impregnation of the above substances with graphite dispersions, there are special treatments for a variety of materials. For example, just as complete assimilation can be obtained in the case of paper by incorporating carbonaceous forms at the time of the former's manufacture, so products like "Cellophane," rayon, Bakelite, ebonite, and synthetic resins can be treated similarly by including colloidal graphite in their respective formulae. Similar treatments also apply to soaps used for industrial lubricating purposes, to nonferrous alloys, and to rubber (latex). Finally, calcined gypsum in water is colored conveniently by incorporating graphite, while waxes are rendered more opaque, conductive,[8] and lubricating.

For convenience in discussing the treatment of common materials, the impregnating medium has been taken as a graphite dispersion throughout, though, naturally, other impregnants are widely employed by industry. From this general case, however, it may be evident that the manufacture of items depicted in Fig. 1 and a variety of similarly impregnated objects, concerns in one manner or another difficulties of impregnation; namely, the presence of occluded moisture, air,

filling agents, surface charge, and general resistance to wetting or ultimate incorporation. To overcome these obstacles, one must resort to physical methods like de-aerating techniques, centrifugal forces, and hydrostatic pressures.

Illustrative of such a procedure, wherein these principles have been adapted to impregnation problems by the physicist, is the so-called Hydewa method[9] which involves a nonuniform pressure pattern on all sides of the object to be impregnated in contradistinction to the usual equalized force under static pressure. It is this unbalanced force, due to variation in pressure, that produces the high rate of penetration so pronounced in securing a positive flow of solution straight through a permeable article. The time required for complete impregnation for certain articles depends on the difference in pressures along a given distance, the penetrability of the article, and the characteristics of the impregnating fluid or compound. In this method air is forced ahead of and replaced by the impregnating fluid. Centrifugal drainage is also combined with impregnation, effecting the uniformity and dependability of many products.

Continued development of impregnation methods using graphite dispersions[10] and other impregnants will be required as industries demand this treatment of more materials. Possibly physicists can suggest the way.

The author is grateful to Dr. F. E. Bartell of the University of Michigan, for assisting in the preparation of this paper. Mr. W. A. Hyde, of the Leon J. Barrett Company and Mr. Raymond Szymanowitz, of the Acheson Colloids Corporation, have kindly granted permission to use extracts from the technical bulletins of their respective companies.

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6. Société Anonyme Le Bois Bakelise, French Patent No. 792,114.
7. M. L. Hartmann, assignor to the Carborundum Company, New York, U. S. Patent 1,573,061.
8. Harold Grossman, U. S. Patent 1,711,482.
9. Bulletin No. 359, Leon J. Barrett Co., Worcester, Mass.
10. Bulletins A260 and B260, Acheson Colloids Corporation, Port Huron, Michigan.

Erratum

Inadvertently, the wrong cut was used for Fig. 1 in Karl F. Herzfeld's article on "The Liquid State" in the May issue. The correct cut appears below.

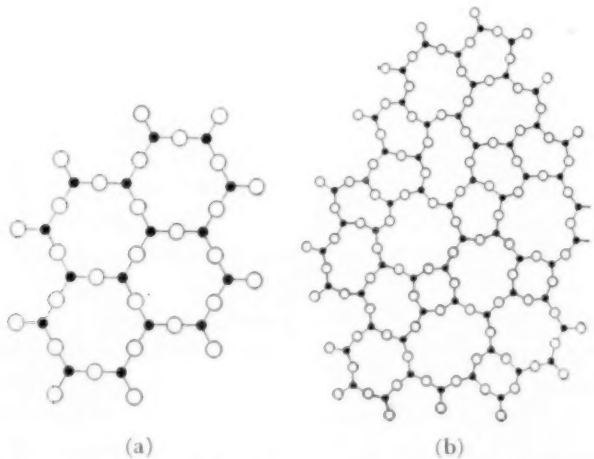

FIG. 1. *Structure of crystal and of glass according to W. H. Zachariasen.*

Here and There

1937 Conference on Spectroscopy and Its Applications

George Eastman Laboratories of Physics,
Massachusetts Institute of Technology

PROGRAM OF PAPERS

Monday, July 19, at 9:30 A.M.: **Spectroscopic Analysis of Materials**

R. A. SAWYER, University of Michigan (with H. B. Vincent). **Rapid Industrial Analysis of Steels.**
J. L. GUION, Watertown Arsenal. **Recent Developments in Metallurgical Spectroscopy at Watertown Arsenal.**
T. A. WRIGHT, Lucius Pitkin, Inc. **The Availability of High Purity Metals for Spectroscopic Purposes.**
A. PORITSKY, Cleveland Wire Works, General Electric Company. **A Stigmatic Concave Grating Spectroscope.**
W. F. MEGGERS, National Bureau of Standards. **Tables of Wave-Lengths for Spectrochemical Analysis.**

Monday, July 19, at 2:00 P.M.: **Spectroscopic Analysis of Materials**

O. S. DUFFENDACK, University of Michigan (with R. A. Wolfe). **The Analysis of Caustic Liquors for Traces of Impurities.**
BOURDON F. SCRIBNER, National Bureau of Standards. **Comparison of Line Intensities in Spectrochemical Analysis.**
MARY E. WARGA, University of Pittsburgh. **Preliminary Study of the Spectrographic Determination of Tin in Steel.**
G. R. HARRISON, Massachusetts Institute of Technology. **Comparison of Grating and Prism Spectrographs for Analysis of Materials.**

Tuesday, July 20, at 9:30 A.M.: **Chemical and Biological Spectroscopy**

FARRINGTON DANIELS, University of Wisconsin. **Spectroscopy in the Study of Reaction Rates.**
CHARLES SHEARD, The Mayo Clinic. **Applications of Spectroscopy, Spectrophotometry and Photelometry to Medical Investigations and Problems.**
K. B. THOMSON, University of Michigan (with O. S. Duffendack and R. A. Sawyer). **The Analysis of Urine and Skin for Traces of Lead.**
G. O. LANGSTROTH, McGill University (with S. A. Komarov and D. R. McRae). **Some Applications of Spectroscopic Methods in Experimental Physiology.**
W. M. URBAIN, Swift and Company. **Application of Spectrophotometry to the Study of Certain Changes Occurring in Hemoglobin Pigments During the Curing of Meats.**

Tuesday, July 20, at 2:00 P.M.: **Spectroscopic Methods**

J. S. OWENS, Dow Chemical Company. **Some Helpful Accessories in Practical Spectrographic Analysis.**
D. RICHARDSON, American Cyanamid Company. **On Boiling Point Determinations by Spectroscopic Methods.**
G. O. LANGSTROTH, McGill University (with D. R. McRae). **Absorption Step-Weakeners of Metallic Antimony.**
D. L. DRABKIN, University of Pennsylvania. **Characteristics of a Monatonic Aluminum Wedge on Quartz, with an Open Density Scale of 30 Centimeters.**
W. R. BRODE, Ohio State University. **Quantitative Spectrographic Analysis by the Logarithmic Sector Method.**

Wednesday, July 21, at 9:30 A.M.: **Spectrophotometry and Related Topics**

W. R. BRODE, Ohio State University. **Influence of Structure on the Absorption Spectra of Organic Compounds.**
D. L. DRABKIN, University of Pennsylvania. **Continuation of Spectrophotometric Studies in the Metabolism and Molecular Structure of Hemoglobin Derivatives.**
E. H. MELVIN, U. S. Bureau of Chemistry and Soils. **A Spectrophotometric Study of the Equilibria in the Gaseous System Nitric Oxide, Nitrogen Dioxide, and Water.**
R. B. BARNES, American Cyanamid Company. **Infrared Spectroscopy as a Tool in Industry.**
FARRINGTON DANIELS, University of Wisconsin. **Chemical Interpretation of Infrared Absorption Spectra (Ethyl Bromide, Acetic Acid).**

Wednesday, July 21, at 2:00 P.M.: **General Spectroscopy and Discussion**

LEWIS H. FLINT, Boyce Thompson Institute for Plant Research. **Immediate Problems in the Light-Sensitivity of Plants.**
LEWIS H. FLINT, Boyce Thompson Institute for Plant Research. **On the Origin of Light Sensitivity in Seeds.**
L. E. GAUL, New York City. **The Importance of the Spectrograph in Establishing the Diagnosis of Argyria or Silver Poisoning.**

Free-for-all discussion of the present status of spectroscopic analysis of materials and of general questions raised by the papers of the conference.

Thursday, July 22, at 9:30 A.M.: **Fundamental Spectroscopy**

BENGT EDLÉN, University of Uppsala. **Spectra of Atoms in High Stages of Ionization.**
W. F. MEGGERS, National Bureau of Standards. **Spectra of Lutecium, Ytterbium and Thulium.**
H. N. RUSSELL, Princeton University. **The Spectrum of Europium (Eu I).**
JULIAN MACK, University of Wisconsin (with Otto Laporte). **The Arc Spectrum of Tungsten.**
W. W. WATSON AND HENRY MARGENAU, Yale University. **Pressure Effects on Spectral Lines.**

Thursday, July 22, at 2:00 P.M.: **Fundamental Spectroscopy**

BENGT EDLÉN, University of Uppsala. **Extreme Ultraviolet Wave-Length Standards.**
J. C. BOYCE, Massachusetts Institute of Technology. **Wave-Length Standards between 2100 and 1600 Angstroms.**
G. R. HARRISON, Massachusetts Institute of Technology. **Present Status of the M. I. T.-W. P. A. Wave-Length Program.**

★

Journal of Applied Physics

For August

Mechanism of Disintegration of Liquid Jets, by P. H. SCHWEITZER

Applications of Physics in Cold Storage, by ARTHUR W. EWELL

Physical Factors Influencing the Design of High Voltage Vacuum Tube Rectifiers, by M. J. GROSS AND Z. J. ATLEE

Physicist and the Incandescent Lamp, by W. E. FORSYTHE

Contributed Research Papers on the Indexing of Powder Photographs, the Electrographic Effect, and on Viscosity of Lubricants under Pressure.

★

Science on the Radio

Climaxing months of intensive planning and a 7000-mile journey for an event lasting little more than three short minutes, a vivid description of the longest total eclipse of the sun in 1200 years was given June 8, 1937 by George Hicks from Canton Island, in the South Seas, over the nation-wide networks of the National Broadcasting Company.

Promptly at 3:00 P.M., EDST, Hicks' voice came through clearly over the complicated radio hookup arranged by the National Broadcasting Company. He described the approaching darkness and the confusion among the great black frigate birds as they settled on the island. Then, as the thin crescent of the sun disappeared altogether behind the moon and the strange phenomenon of the solar corona —luminous gases enveloping the planet—sprang into view, Hicks gave a word picture of the scene from the top of a temporary radio shack built on the tropical island. From that point for the full three minutes and thirty-three seconds of totality Hicks gave to the world a description of the beauties of mysterious pearly light around the sun, and the great domes and streamers that are linked with the flaming body.

★

New Appointment

The laboratory staff of the Clough-Brengle Company, 2815 W. 19th Street, Chicago, manufacturers of electrical testing equipment, has recently been augmented by the addition of Dr. Maxwell R. Krasno, formerly research physicist in the department of physiology of the University of Wisconsin. Dr. Krasno will be associated with Kendall Clough in the further development and refinement of Clough-Brengle electronic instruments.

★

The Ohio Academy of Science and the Ohio Physics Club held a two-day meeting at the Ohio State University. The program was as follows:

Friday, May 14, 1937

Zeeman Effect Studies in Neon. J. A. PEOPLES, JR., *Ohio State University*
Intensity Measurements in the Calcium Spectrum. JACK SMITH, *Ohio State University*
A Search for the Spectrum of Doubly Excited Helium. F. P. BUNDY, *Ohio State University*
Variate Atom Equipoints and Mixed Crystals in Their Relation to Space-Group Theory. F. C. BLAKE, *Ohio State University*
The Absorption Spectra of Pure Chlorophyll *a* and *b* in Ether Solution. H. V. KNORR AND V. M. ALBERS, *Antioch College*
The Absorption Spectrum of Chloroplasts in Living Cells. H. V. KNORR AND V. M. ALBERS, *Antioch College*
Frequency Measurements in the Elementary Laboratory. WILL C. DOD, *Miami University*
Phase Changes in Resonant Circuit and Effect of Polarized Light on a Photronic Cell. ALVA W. SMITH, *Ohio State University*
The Infrared Absorption Spectrum of the Deuterium and Selenides. WILLIAM C. SEARS, *Ohio State University*
Stars with Composite Spectra. J. A. HYNEK, *Perkins Observatory*
Stereoscopic Projection with Polarized Light. ERNEST GINSBERG, *Ohio State University*
A Puzzle Demonstration in Polarized Light. R. L. EDWARDS, *Miami University*
The American Physical Society. JEROME B. GREEN, *Ohio State University*

Saturday, May 15, 1937

Improved Apparatus and Techniques for the General Laboratory. R. L. EDWARDS, *Miami University*
Making Stresses Visible. ROYAL WELLER, *Ohio State University*
A Lightning Flash and Its Components. JOHN G. ALBRIGHT, *Case School of Applied Science*
Cross Hairs. RICHARD H. HOWE, *Denison University*
An Empirical Equation for Loudness. H. P. KNAUSS, *Ohio State University*
The Addition of Two Frequencies in Audio Apparatus. DARRELL B. GREEN, *Ohio University*
The Viscosity of Sols Made from X-Irradiated Substances. C. HARRISON DWIGHT AND H. KERSTEN, *University of Cincinnati*
Some Results on Galactic Structure and Dark Nebulae. FREEMAN D. MILLER, *Swasey Observatory, Denison University*
Intensities of Forbidden Lines in the Spectra of Novae. N. T. BOBROVNIKOFF, *Perkins Observatory, Ohio Wesleyan University*
Water Analogues in Electricity. P. E. MARTIN, *Muskingum College*
Vacuum Tube Circuits. JOHN GREGORY, *Muskingum College*
Telescope Mountings. NOLAN BEST, *Muskingum College*

Presentation of Franklin Institute Medals

At a recent meeting at the Franklin Institute the following medals were presented:

Franklin Medals: Dr. Robert A. Millikan and Dr. Peter J. W. Debye.

Cresson Medals: Dr. Carl D. Anderson of the California Institute of Technology; Dr. William Bowie, retired chief of the United States Coast and Geodetic Survey; Jacques Edwin Brandenberger of Neuilly-sur-Seine, France; Dr. Ernest O. Lawrence and Dr. William F. Giauque of the University of California.

Longstreth Medals: Dr. Emile Monnin Chamont of Cornell University; Richard T. Erban of New York; John S. Haug of Philadelphia; Harold Sinclair of Middlesex, England; and Herbert L. Whittemore of the National Bureau of Standards, Washington.

Henderson Medal: Dr. Rupen Eksergian of Philadelphia.

Levy Medal: Professor Inge Lyse of Lehigh University.

Potts Medal: Dr. John Clyde Hostetter of Hartford, Connecticut.

★

Statistical Methods of Quality Control

During the present year, the Department of Economics and Social Science of the Massachusetts Institute of Technology has introduced a new graduate subject in Statistical Methods for Quality Control. This action constitutes another step in the rapid progress of this relatively new field of applied statistics. Although the laws of chance have been successfully applied to many fields—as for example, astronomy, physics, gambling and agricultural experimentation—it was not until the twenties that they were effectively used to control the quality of manufactured products. Dr. Walter A. Shewhart and his associates at the Bell Telephone Laboratories pioneered in this applied research, but up to 1931 much of the fruits of their labor remained with the Telephone Company. In that and the following years, however, with the publication of Dr. Shewhart's treatise, with the awakened interest of highly competent English statisticians, and ready industrial cooperation through the American Society for Testing Materials, the American Standards Association, the American Society of Mechanical Engineers and the British Standards Association, the possibilities of this technique became more generally appreciated. Although actual installation of quality control programs still remains few, the future of the field is sufficiently certain to warrant its inclusion in the Technology curricula. This expectation of permanency is well supported by isolated but highly successful applications to such variable quality products as coal, coke, cotton yarns, cotton textiles, woolen textiles, manufactured gas, lamps, spectacle glass, war products and building materials.

The purpose of the course introduced at M. I. T. is to provide the student with the background of mathematics, economics and engineering testing necessary for successful work in quality control. That this background is necessary is clear from the nature of the field itself.

Quality control follows from the fact that in ordinary manufacture, the units of a product are far from identical,

since the cost of making all units approximately identical would be unwarranted in terms of the uses and value of the product. Some variation in quality is thus conceived as economically justifiable and it is the purpose of a quality control program to develop statistical methods of measuring and describing the actual quality distribution, to ascertain the proper economic limits to such variations and to suggest ways and means of facilitating allocation and correction of production troubles when these limits are exceeded. The subject thus naturally embraces an analysis of economic value, a presentaton of the basic theory of probability, sampling and ordinary statistical methods and finally a consideration of plant production processes, testing, setting of specifications and standards, determination of indexes of quality, etc. Economic, mathematical and engineering ability are accordingly all needed by those who expect to handle industrial problems dealing with quality statistics.

M. I. T. had the advantage during the year of hearing from practical workers in this rather new field. Notably, Dr. A. Ray Olpin, of the editorial staff of this journal, Captain Leslie Simon and Mr. Donald Beeman of Picatinny Arsenal, and Mr. A. G. Ashcroft of the Alexander Smith & Sons lectured on the present uses and possibilities of this technique in the manufacture of cotton textiles, war materials and rugs.—H. A. FREEMAN.

Prize to Young Authors

The *Electrochemical Society* has awarded to Mr. William A. Johnson, of Pittsburgh, Pennsylvania, the society's "Prize to Young Authors," for the paper published jointly by Mr. Johnson and Professor Allison Butts entitled, "Studies of Overvoltage: The Effect of Fusion of the Cathode and the Effect of Temperature on Gas Polarization." Mr. Johnson at present holds the Molybdenum Company's fellowship in metallurgy at the Carnegie Institute of Technology, where he is investigating the heat treatment characteristics of tungsten steels.

★

Physics in the Canning Factory

In a recent issue of the periodical *Western Canner and Packer*, there appeared an article by Dr. Willi M. Cohn and one by E. A. Kent describing recent developments in artificial lighting. In the canning industry, the color of artificial illumination is especially important because use is made of small differences in color in sorting fruits and vegetables. Suggestions for the best kind of lighting for sorting and observing blemishes are made.

Archer Hoyt

PAUL D. FOOTE, ***Gulf Research and Development Company***

Archer Hoyt of the Gulf Research and Development Company, Pittsburgh, Pennsylvania, died suddenly the evening of June 12, 1937 from an embolus following, after nearly two weeks, an appendectomy. Dr. Hoyt was born in Washington, D. C., November 26, 1905, as the second child of Rev. and Mrs. J. W. Hoyt. He was graduated by Walla Walla High School, Washington, in 1923, and by Whitman College in 1927, receiving the degree A.B. magna cum laude. At this time he entered California Institute of Technology as a graduate student and assistant in physics. In 1931 he was awarded a doctorate degree and during this period he was engaged with Dr. J. W. M. DuMond in x-ray spectroscopy, which resulted in five publications, including the development of a double crystal spectrometer and a stereoscopic fluoroscope. Following graduation he spent the summer of 1931 as a construction engineer with the Rockefeller Foundation in Philadelphia where he continued his work on the stereoscopic fluoroscope. In the fall of 1931 he became an instructor in physics at Cornell University, publishing two papers on x-rays.

Archer Hoyt

Dr. Hoyt joined the Gulf Laboratory in 1932 and from that time until his death he was engaged primarily in the development of gravity measuring instruments, a field in which he was highly successful and had attained a remarkable record of accomplishments. He published an article on "A New Type of Interferometer" in 1936 and another on an "Optical Slit" in 1937.

Dr. Hoyt was an exceptionally brilliant experimental physicist, especially in the field of instrumental design. A splendid future lay before him, but even with his untimely death at the age of thirty-one, he had built, through his scientific achievements, a permanent monument to his memory. He was a member of Phi Beta Kappa, Sigma Xi, American Physical Society, and Pittsburgh Physical Society. He is survived by his wife, Lenore Martin Hoyt, a graduate of Whitman College, 1927, and of Cornell, M.A., 1932.

Innovations in Instruments

Hydrogen as Cooling Agent

A new General Electric turbine-generator is to be installed in the River Rogue Plant of the Ford Motor Company. It will be a 110,000 kilowatt unit and will be cooled with hydrogen. Hydrogen, when used as a circulating medium in large generators, reduces windage losses to 10 percent of what they would be with air, and this results in an improvement in the efficiency of the generators of from 0.6 to 1.1 percent, depending upon the size and r.p.m. of the units.

Hydrogen requires considerably less pressure to circulate the necessary volume, and it has many times the thermal conductivity of air. It also removes more heat from a given surface for the same temperature drop. The circulating hydrogen is cooled by fin type coolers located within the generator framework. This construction results in a very compact installation as the large housing and the surface air coolers, external to the framework, can be dispensed with.

★

Diffusion of Hydrogen through Metals

The diffusion of gas through a piece of solid metal, so slowly that only one cubic inch of the gas passes through in a hundred thousand years, can be measured, according to Dr. Francis J. Norton of the General Electric Research Laboratory. The method of measurement introduces a new application for the all-metal vacuum tube.

Ordinarily it is considered that a metal container is gastight, provided its seams are tight. Hydrogen, however, slowly escapes through metal, even of appreciable thickness. In his paper, on "Diffusion of Hydrogen from Water through Steel," Dr. Norton pointed out that, in high pressure steam boilers, at a temperature of about 575 degrees Fahrenheit, water and iron react to produce iron oxide and hydrogen. The iron oxide forms black scale on the tubes of the boiler; some of the hydrogen escapes as gas within the tubes, some combines with oxygen dissolved in the water, and the rest diffuses through the steel. The reaction occurs even at room temperature, but is greatly speeded up as the pressure and temperature are increased.

A detector amplifier triode metal vacuum tube was used by Dr. Norton for observing the hydrogen flow. It is a small, evacuated volume within steel walls, and in it are a plate, grid, and filament—the elements used in ionization gauges to measure gas pressures. In the circuit, the grid is the most negative and hence positive ions flow to it. The number of positive ions is proportional to gas pressure, so the grid current is a measure of gas pressure.

The metal vacuum tube ordinarily has a coating of protective paint, and this was sandblasted off for most of the experiments. The tube shell was then dipped into water at different temperatures and for different lengths of time, and the grid current measured. The measurements showed that, at 78 degrees Fahrenheit, hydrogen entered through the 30-mil steel shell at a rate of one-tenth of a micron per hour, which is about one cubic inch of gas per thousand years. The gas which passed through the steel was analyzed and found to be extremely pure hydrogen.

Addition of one-tenth of one percent of sodium chromate to the water, known to inhibit corrosion, was found to stop the penetration of hydrogen through the steel. Dr. Norton found it impossible to measure any penetration, and his equipment was capable of measuring as little as one cubic inch of gas per hundred thousand years. Various coatings were applied to the tube and the rate of diffusion determined. The regular paint as applied to the radio tubes was found to be the best protection. Various other coatings lowered the rate of diffusion somewhat, but a few coatings —such as zinc, or porous copper plating, or sodium silicate —caused increased diffusion. Stainless steel was found to give a very much lower rate than ordinary steel, and tubes with composite walls of different metals were found to have different diffusion rates.

Tests made in atmospheres of varying humidity, even up to the point of complete saturation at 78 degrees Fahrenheit, showed no measurable diffusion of hydrogen from the water vapor surrounding the tube; liquid water itself, Dr. Norton reported, is essential for producing measurable diffusion. The fact that the tubes do not let in any hydrogen from the air shows that the amount of free hydrogen in the air must be very minute in amount, he said.

★

Automatic Radio Devices

¶ The United States Senate passed on March 23 the amendment to the 1934 Communications Act, making it possible for the Cruft Laboratory at Harvard University to resume experiments in automatic radio devices that offer high promise for use in police protective work and in other fields. The 1934 law made it necessary for the Cruft station to shut down for lack of a licensed operator. The Cruft Laboratory had been employing an automatic device capable of preventing improper operation of the station, and informed the Federal Communications Commission that it could not afford to keep an operator on duty throughout continuous operation. The amendment authorizes the commission to make special regulations governing the use of automatic radio devices.

Science, April 2, 1937.

Coiled-coil Filaments

A new development announced by the Mazda Lamp Laboratories is what is known as the coiled-coil filament. As is well known, the filaments in the ordinary gas-filled lamps are wound into a coil. In this latest development, the coil itself is wound into a second coil which reduces the power lost to the gas enclosed in the bulb. A ten percent increase in the efficiency results from this improvement. It is also said that the candlepower is better maintained throughout the life of the lamp. It has been calculated that the savings to all of the users of Mazda lamps will be in the neighborhood of $10,000,000 per year as a result of this new development.

★

Recent Research in the Bell Laboratory

Reprinted from Annual Report to the Stockholders

"A change of emphasis in research and development work during the depression resulted from the lessened demand for new plant and equipment. Research and development problems cover the entire range from those which must be solved immediately, because of urgently needed new plant and equipment or because of specific difficulties which arise in the current operation of the service, to problems of a fundamental character which lie at the roots of continued improvement in communication service.

"During the past few years, emphasis has been on fundamental research and development, and viewed from the standpoint of a more extended, better and more economical communication service, it seems from what has been accomplished that these years may have been prospectively more productive than any corresponding period since the inception of the business.

"During 1936, research and development work has gone forward on many new things which are potentially important to the business in the future. Also substantial progress has been made towards completion for commercial use of new subscribers' equipment, new forms of central office switching machinery, new applications of multi-channel high frequency methods of transmission over circuits of the conventional type, a radically new form of transmission circuit—the coaxial cable—and certain aspects of radio telephony.

"The service trials of the new subscribers' apparatus have been substantially completed and work is under way to make these instruments generally available.

"Further research and development work on the improved switching mechanism has been pushed vigorously during 1936, not only in the direction of completing a large central office service trial installation but likewise in the direction of applying the new mechanism elsewhere where switching problems exist. A new private branch exchange employing this apparatus has been under trial for several months and it is expected that manufacture for general use will be started during 1937. Likewise, work has been undertaken in the direction of application in the field of toll line switching.

"In the field of broad band carrier systems, the research and development work has now reached the point where trial installations of commercial forms of such systems for use on cable and open wire circuits are being made. In the case of cable circuits, the system is planned to yield twelve telephone circuits from two pairs of wires. While not all of the pairs in existing cables can be equipped simultaneously with this multiplex system, its introduction will permit increasing the message-carrying capacity of the existing longer cable routes several fold, the carrier system being applied to the longer circuits and existing voice frequency methods to the shorter circuits. In the case of open wire circuits, the new systems when applied will yield a total of sixteen telephone circuits for each pair of wires.

"The initial trial installation of coaxial cable between New York and Philadelphia was completed in the fall of 1936 and extensive experiments are under way. Thus far the results have confirmed anticipation and, while there is still a large amount of research and development work to be done, there is every reason to believe that this radically new and very simple form of communication circuit will in the future have wide application, particularly over the longer high traffic density routes.

"All of these accomplishments in the application of high frequency broad band technique are the result of years of development work extending uninterruptedly through the whole period of the depression.

"During 1936, plans were initiated for materially increasing the effectiveness of the transatlantic short wave radio circuits. As a result of research work in the Bell Telephone Laboratories, single sideband operation, highly directive receiving antennas and new transmitting antennas have been developed, and it is expected that during the current year they will be applied gradually. They will materially better the performance of transatlantic telephone circuits and reduce the out-of-service time due to adverse atmospheric conditions.

"A large further trial installation of buried wire underground distribution for rural service was made in 1936. Several hundred miles of the new wire have been installed by means of a special plow which buries the wires along highways and into premises with comparatively little disturbance of the ground surface. Unless something now unforeseen occurs, this new system bids fair to have large and advantageous use."

★

New Midget Cathode-Ray Oscillograph

Recent development of a new cathode-ray tube with a one-inch screen and greatly reduced voltage requirements now makes possible the design of an extremely compact cathode-ray oscillograph. The model 105, just announced by the Clough-Brengle Company of 2815 W. 19th St., Chicago, Ill., offers the electrical and testing features of larger instruments, yet measures only 9″×9″×9½″ and weighs 16 lb. This instrument is complete with a thyratron controlled self-synchronizing linear timing axis generator, input amplifiers for both horizontal and vertical plates, and power supply for operation from line voltages. A complete description of the instrument may be secured by writing the manufacturer and mentioning this publication.

New Photographic Lamp

Mercury vapor, long the ally of photographers, is again being utilized in a new photographic lamp now under development in the Mazda Lamp Laboratories, according to an announcement by the lamp division of the Westinghouse Electric & Manufacturing Company, Bloomfield, N. J.

This new light source, which will later be known commercially as the Flood-Flash lamp, is similar in appearance to some of the high intensity mercury vapor lamps now on the market in that it consists of a bulb within a bulb. It has an over-all length of approximately 6″ and a diameter of approximately 1½″. Under continuous operating conditions, the lamp consumes about 100 watts, producing 3000 lumens. However, by operating it in conjunction with special equipment, high momentary current discharges may be passed through it resulting in a flash at peak brilliancy of about 500,000 lumens with an average brilliancy of 300,000 lumens.

The flash may be so controlled as to be timed with the opening of a camera shutter, thus making possible the utilization of a light of high intensity and great actinic value at the instant the photograph is taken.

At the present time, the Flood-Flash lamp is not available commercially since further development on it is necessary. When perfected, this lamp may be used for general lighting of a studio while posing the subject and focusing the camera and then may be flashed for the actual photograph. The same lamp may be flashed as often as necessary.

★

Schering Capacitance Bridge

The General Radio Company announces a new audio-frequency Schering capacitance bridge, direct reading in both capacitance and power factor. Capacitances up to 1μf and power factor up to 6 percent (0.06 expressed as a ratio) can be read directly from the dial of the instrument. This range is said to embrace most of the capacitances met in communication engineering: paper condensers, cables, slabs of solid dielectric, liquid in large cells, and ground capacitances of generators and transformers. The accuracy over the direct-reading range is, for capacitance, $\pm 2\mu\mu$f for the air capacitance range (100 to 1100$\mu\mu$f), and $\pm 2\mu\mu$f multiplied by the decade multiplier setting for higher values. For power factor, the accuracy is ± 0.0005 or ± 2 percent of the dial reading. The power factor dial is calibrated in power factor at 1 kilocycle. Other frequencies between 60 cycles and 10 kilocycles can be used, and power factor is obtained by multiplying the dial reading by the frequency in kilocycles.

Other types of capacitance bridge circuits can be used with this instrument, as, for instance, series and parallel resistance arrangements, by adding external resistors and precision condensers. This flexibility, combined with the high accuracy and direct-reading feature, makes the bridge acceptable for a wide field of application.

★

Aerodynamic Microphone

An aerodynamic microphone which combines compactness, excellent fidelity and novel streamlined appearance has been introduced by the RCA Commercial Sound Section. Of the pressure-operated type, the RCA aerodynamic microphone was designed to fit a wide variety of public address and "close talking" applications. With a frequency range of from 100 to 6000 cycles it is particularly fitted for natural tone reproduction of both speech and music. Being impervious to ordinary temperature, humidity and barometric pressure changes, and of a rugged construction, the new microphone is also suitable for outdoor use.

The aerodynamic microphone is small enough to fit into the hand and weighs only a pound and a half. It measures 2⅝″ wide, 3″ high and 3⅜″ deep. External excitation or power is unnecessary. It operates at an impedance of 250 ohms and is completely shielded against r.f. or a.c. fields.

★

The Westinghouse Technical Press Service announces that both the sodium and mercury vapor lamps are well rooted and will continue gradually to take their place as supplemental to Mazda incandescent lamps in certain fields of usage.

During 1936 there were perhaps better than 35,000 new mercury lamp sockets placed in service which, added to an estimate of some 16,000 new sockets in 1935, would total something more than 50,000 mercury lamps in service at the beginning of 1937. One is led to expect a continuous rise in mercury lamp usage especially since the fields of color floodlighting and of street lighting are almost wholly undeveloped. To date sodium vapor lamps in this country have been limited to the two sizes, namely, 6000 to 10,000 lumen, and almost altogether to the field of highway lighting. It has been estimated that some 2000 sodium lamp sockets went into service last year and something less than one half of that number during the preceding two years.

This progress may be compared with the usage of the mercury lamps for highway lighting in England, where some 1000 miles of highway are well illuminated with no fewer than 30,000 units.

Booklets Received Recently

Dust Counter (4 pp.). Fields of view showing how easily dust counts can be made with this counter are given. Many illustrations show the outer appearance of this instrument. Bausch and Lomb Optical Company, Rochester, N. Y.

Test Equipment, Accessories and Parts (36 pp.). New RCA equipment is described in this booklet. Some of the items are cathode-ray oscillograph, test oscillators, a.c. bridges beat frequency oscillators, microphones, phonograph equipment and replacement parts. RCA Manufacturing Co., Camden, N. J.

Some of the New Books

Controlled Reading. A Correlation of Diagnostic, Teaching, and Corrective Techniques. EARL A. TAYLOR. Pp. 367+xxviii, Figs. 101. The University of Chicago Press, Chicago, 1937. Price $3.50.

This interesting book summarizes the work done at many laboratories in recording and studying the movement of the eyes during reading and in developing methods for correcting faulty reading habits. The results of tests are usually expressed in terms of words read per minute and the number of fixations and regressions for a paragraph taken from some story. Comprehension is judged by four or five true-false questions. Occasionally the effects of muscular imbalances are noted on the records, but usually the defects noted are due to bad habits. Equipment and methods for teaching reading and for corrective training are discussed and illustrated with many case histories showing prompt and permanent improvement. Considering that reading for instruction or entertainment is a life-long activity, it is important to learn to read efficiently. Two commercial devices called the "Ophthalm-O-Graph" and the "Ophthalm-O-Scope" were used in most of the clinical work with school children. (It is interesting to speculate as to the reasons for the silly spelling.)

The point is made that scholastic failure is largely due to faulty reading. One thinks of similar claims made in the name of poor teeth, tonsils, eyes, ears—anything to draw attention from differences in native intelligence and interest in things intellectual. In the present instance the tabulated difference between groups of successful and unsuccessful high school students does not seem to be enough to explain the difference between success and failure, although there are striking individual cases. On the average, it would seem that a slightly greater ambition and energy would easily overcome the handicap of about 6 percent in reading speed. Of all studies, it seems odd that mathematics, in which practice is so important, should be selected for a detailed investigation of the correlation between faulty reading and unsuccessful work. One wonders if it can also be proved that slow reading of instruction books and rule books can explain why some people never learn to break 80 at golf or to make the football team.

On the whole, the book gives a compilation of some valuable scientific results as to eye movements in reading, and gives an effective method for correcting faulty reading. But it seems that an attempt is made to explain too much by means of small, easily compensated, differences in performance.

JOSEPH VALASEK
University of Minnesota

Atomic Structure of Minerals. W. L. BRAGG. Pp. 295 +xiii, Figs. 144. Cornell University Press, Ithaca, N. Y., 1937. Price $3.75.

During the spring semester of 1934, Professor W. L. Bragg was the George Fisher Baker nonresident lecturer at Cornell University. The material which he presented during these lectures is largely that contained in his first volume of *The Crystalline State*. As following the custom of publishing a summary of these lectures in book form would merely repeat material already available in such form, Professor Bragg has chosen instead to give a summary of the results of x-ray investigations of the structures of minerals.

The first part of this book, consisting of three short chapters, is a condensation of the relevant parts of *The Crystalline State*, intended to form a theoretical background. As is usually the case with summaries of this sort, the reader who is unfamiliar with the methods of x-ray diffraction analysis would profit more by reading the original source, and one who is conversant with these methods will probably gain little by reading the summary.

The second and major portion of the book contains a descriptive review of the atomic structures of those minerals which have been studied up to the close of 1936. Such a summary could easily become merely a tabulation of data, but this Professor Bragg has carefully avoided. He has sought, as far as possible, to point out the relations existing between various structures. Pauling's coordination rules constitute an important foundation for these relationships, and naturally these rules supply the unifying background of this book. The structures are illustrated by perspective drawings, photographs and sketches of models, and projections upon important crystallographic planes. The classification of the structures is that usually employed in mineralogy textbooks, except where the x-ray results have indicated this to be erroneous. As far as possible, the formula, space group, contents of the elementary cell, axial lengths, and axial elements are given for each mineral so far investigated. This book may appear to crystal structure workers to be lacking in that atomic positions are not given except as they are shown as heights above projection planes; admittedly, the inclusion of these data would considerably increase the size of the present volume. Extensive references are given to the original reports of the determinations of these structures.

VICTOR HICKS
Westinghouse X-Ray Company,
Long Island City, N. Y.

Television Reception. MANFRED VON ARDENNE (Translated by O. S. Puckle). Pp. 121, Figs. 96. D. Van Nostrand, New York, 1936. Price $2.75.

This book includes chapters on the following subjects: the technical problem of television; constructional features and operation of electrostatically focused cathode-ray tubes; power supplies; construction and operation of a television receiver and a discussion of the results obtained.

Because of the variety of topics dealt with and the large amount of space devoted to illustrations, the treatment of the technical aspects of television reception is rather sketchy, especially in the sections dealing with radio-frequency, video and audio-circuits.

Mathematical equations and derivations are avoided and the author limits himself to a simple description of the problems of television reception and his own experiments looking toward their solution. While the statements made in the book are in general quite accurate there are many places where a more complete explanation of the principles involved would be helpful to the casual reader.

The television receiver described was designed to be used on 240 lines at 25 pictures per second and would be inoperative for the 441 line, 30 picture interlaced transmissions now being broadcast experimentally in this country. No attempt was made to combine the sound and video receivers in a single cabinet with a single tuning control. The sound receiver consisted of a feedback detector and three stages of A. F. amplification. For these reasons and the fact that foreign tubes and components not readily available here are used, the book cannot be recommended as a guide to prospective American constructors of television receivers.

The outstanding feature of the book is the excellent collection of photographs of actual cathode-ray phenomena which illustrate the various types of distortion which may occur in television images. Students, technicians, and perhaps some engineers who have not yet had the opportunity to experiment with television receivers will find these photographs helpful in familiarizing themselves with the kinds and sources of image distortion encountered in television reception.

F. J. SOMERS
Farnsworth Television Inc. of Pennsylvania

Electrical Measurements. Precise Comparison of Standards and Absolute Determination of the Units. HARVEY L. CURTIS. Pp. 302+xiv, Figs. 56. McGraw-Hill Book Company, New York, 1937. Price $4.00.

This book is a valuable, authoritative addition to the International Series in Physics. It makes available the technique that has been developed for the precise comparison of electric standards and for the absolute determination of the electric units. It considers in detail the construction of electric standards and all known sources that may introduce into the final result an error as large as one part in a million. While other methods are described, only one or two of the best for each unit are given complete analysis. In a few cases where precision methods have not been developed, new methods that promise high precision are outlined.

A large portion of the book deals with the establishment of concrete units of resistance, capacitance and inductance, and with the problems bearing on their construction and use. The absolute measurement of an electric current, too, is considered in detail, while that of electromotive force and the derived units are given relatively much less space.

In order to estimate the accuracy with which the magnitudes of the units can be determined, the theory underlying each method is developed and the possible errors in experimental and construction procedure are analyzed.

The book also defines the electric units and gives their history. It devotes two chapters to the consideration and measurement of the fundamental and derived mechanical units, because the attainable accuracy in electric measurements is limited by that with which these can be made. It contains a wealth of valuable, authoritative information on matters applicable to nearly all kinds of electric measurements of precision, and is indispensable to those who desire to understand the technique of such measurements.

It is a well-written and well-illustrated book and makes a valuable addition to the library of every physicist and advanced student of physics.

ANTHONY ZELENY, *University of Minnesota*

Electricity and Magnetism. An Introduction to the Mathematical Theory. A. S. RAMSEY. Pp. 267+xi, illustrated. Cambridge University Press, Cambridge, 1937. Price $3.25.

The first thing to catch the reader's attention on perusing this intermediate text on electricity and magnetism is that the subject of electromagnetic induction is not reached until within fifteen pages of the end of the book. In fact the electric current does not make its appearance until page 148. This lack of balance in the selection of material may be due to the fact that the text is primarily concerned with "the needs of candidates for Part I of the Mathematical Tripos."

In order to avoid the concept of action at a distance the author bases the subject of electrostatics, to which over half the book is devoted, on Gauss' law of electric flux rather than upon Coulomb's law of force. He feels that "modern views" require the introduction of an ether, but he is chary about ascribing physical properties to it. It is rather disconcerting to read that electric displacement consists of an actual displacement of electricity and to find Gauss' law for a dielectric deduced from this definition, when modern views would attribute only that portion of the displacement known as the polarization to the motion of charge.

Electrostatics is treated in considerable detail, and the magnetic fields of steady currents in less detail. A number of examples are worked out in the body of the text, and a large number of problems, many of them of geometrical rather than of physical interest, are placed at the end of each of the eleven chapters. Only geometry and elementary calculus is used. The book may be found useful as a text for drill in the solution of problems, but it leaves much to be desired as an exposition of the theory of electromagnetism.

LEIGH PAGE, *Yale University*

Dielectric Phenomena in High Voltage Cables. D. M. ROBINSON. Pp. 174+xii, Figs. 96. Instruments Publishing Company, Pittsburgh, 1936. Price $5.00.

This 168-page monograph summarizes in a very interesting manner recent researches leading to a better understanding of the mechanisms of failure of cables insulated with tightly wound strips of wood pulp paper impregnated with fairly viscous mineral oil or oil-rosin mixtures. Such cables are used very extensively for underground power transmission up to 66 kv. The monograph is written for practical men. It contains only sufficient theory to ensure an understanding of the necessary language and concepts. It is mainly descriptive and is adequately illustrated with diagrams and photographs.

The principal emphasis of the monograph is the presentation of the experimental facts leading to a knowledge of several distinct types of failure, namely—disruptive breakdown, tracking, and thermal instability. Of these the tracking failure is the most common, and observant investigators have demonstrated that such failures start from local spark discharges in low pressure gas pockets or "voids" in the spaces between paper tapes at either the conductor or the sheath—usually at the former where the electric stress is highest. These discharges gradually progress through or around the paper tapes, decomposing the oil, generating gas and polymerization products called "wax," and leaving conducting carbon "tracks." Such a process eventually causes failure even though the average electric stress is but a fraction of the initial disruptive breakdown strength of the insulation.

On the whole, this book provides an excellent example of how resourceful experimenters can devise means for studying undesirable phenomena (such as electric failure), determine their causes and thereby indicate their remedies.

One criticism may be worth noting. In the opinion of the reviewer the author did not give sufficient credit to the "oil-filled" cable system originally developed by Emanuelli, which provides a continuous supply of low viscosity liquid sufficient to prevent void formation and allow successful operation for the same thickness of insulation at more than double the voltage at which the "solid type" cable will operate.

HUBERT H. RACE
Research Laboratory,
General Electric Company

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Recent Booklets

Less Noise, Better Hearing, 3rd Edition (60 pp.) 1937. The contents of this booklet are (1) Selecting an Acoustical Material, (2) Celotex Acoustical Products, (3) Noise Quieting, (4) Acoustical Correction, (5) Radio Studios. The physicist will find much of interest in this carefully prepared booklet. Published by the Celotex Corporation, 919 N. Michigan Avenue, Chicago, Ill.

A New Source of Artificial Daylight (4 pp.). This booklet describes a new gaseous discharge lamp using carbon dioxide. Luminosity curves are given which indicate an average spectral distribution very similar to that of daylight. Barkon Frink Tube Lighting Corporation, Bridge Plaza Square, Long Island City, N. Y.

Spectrograph (4 pp.). This booklet describes a grating spectrograph which is said to bring greater speed and higher accuracy at a much lower cost and operating expense than other spectrographs. Many unique features in the design of this spectrograph are described. Applied Research Laboratories, 1240 S. Main Street, Los Angeles, California.

Temperature Control (1 page). Temperature controls and limit switches for temperatures up to 1400°F are described. Burling Instrument Co., Newark, N. J.

Among our Contributors

Hugh M. Smallwood received the B.S. and Ph.D. degrees from the Johns Hopkins University in 1924 and 1927, respectively. After teaching in that institution for two years, he was instructor in chemistry at Harvard until 1934. Since that time, he has been a member of the research staff of the General Laboratories of the United States Rubber Products, Inc.

Leonard B. Loeb was born in Zurich, Switzerland, September 16, 1891. He received his S.B. degree from the University of Chicago in 1912 and his Ph.D. in physics from the University of Chicago in 1916. He was at the National Bureau of Standards from 1916 to 1918. From 1918–19 Professor Loeb was in the air service, A.E.F. and later liaison officer, French anti-aircraft sound locators. He was National Research Fellow at the University of Chicago from 1919 to 1923. Since 1923 he has been at the University of California, first as assistant professor and now as professor. His chief work is in the field of electronics, conduction in gases, ion mobility, recombination, spark discharge, electron attachment, electron mobilities.

Contributed Original Research

The Use of the A.S.T.M. Penetration Equipment for Estimating the Viscosities of Materials of High Consistency

E. O. Rhodes and E. W. Volkmann
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(Received April 26, 1937)

In a recent publication Thelen described experiments in which the standard penetrometer was used to determine the flow-shear diagrams for a number of asphalts. On the basis of these diagrams Thelen calculated viscosities which are of different magnitude from those expected from Saal's formula. In the present paper certain fallacies in Thelen's deductions are pointed out. A new method for analyzing Thelen's experimental results is shown which makes it possible to calculate absolute viscosities from penetration readings for a series of successive time intervals. The method is based upon the determination of viscosity by axial displacement of concentric vertical cylinders. Since the conditions under which viscosity can be determined by axial displacement are only approximated in the penetration test the new method cannot be expected to have a high degree of accuracy. Nevertheless from successive penetration readings on a coal tar pitch (penetration 100 g, 5 sec. at 25°C) an average viscosity of 383,000 poises was calculated which closely agrees with the value of 380,000 determined by a capillary rise viscometer. The viscosity as calculated from the initial penetration reading by the Saal formula was 355,000 poises.

THE conversion of penetration measurements, made in accordance with A.S.T.M. Standard Test Method D 5–25, into absolute viscosity units is a problem which has received attention from a number of investigators. Saal and Koens[1] studied the penetration-viscosity relationship of two steam distilled asphalts and as a result of their investigation proposed the empirical formula

$$\eta \text{ (poises)} = (5.13\times10^{9})/(\text{penetration})^{1.93}.$$

Traxler, Pittman and Burns;[2] also Traxler and Pittman[3] have questioned the general validity of the Saal formula. On the other hand Pfeiffer and van Doormaal[4] used Saal's formula as a basic factor in a system for evaluating the relation between apparent viscosity and temperature. They also proposed a method in which penetration measurements are employed to estimate the degree of plasticity of the material under test. In a recent publication Thelen[5] described experiments in which the standard penetrometer was used to determine the flow-shear diagrams for a number of asphalts. On the basis of these diagrams Thelen calculated viscosities which are of entirely different magnitude from those expected from Saal's formula.

It is the purpose of the present paper to point out some fallacies in Thelen's deductions and to indicate a method for analyzing Thelen's experimental results which makes it possible to calculate absolute viscosities.

Thelen states: "For any plastic solid, $m = a/(b-f)$ when m = mobility in reciprocal poises, a = rate of flow in cm³ per sec., b = shearing stress in dynes per cm², and f = yield value in dynes per cm². If $f=0$, the material is a liquid whose

[1] R. N. J. Saal and G. Koens, J. Inst. Petrol. Tech. **19**, 176 (1933).
[2] R. N. Traxler, C. U. Pittman and F. B. Burns, Physics **6**, 58 (1935).
[3] R. N. Traxler and C. U. Pittman, J. App. Phys. **8**, 70 (1937).
[4] J. P. Pfeiffer and P. M. van Doormaal, J. Inst. Petrol. Tech. **22**, 414 (1936).
[5] E. Thelen, J. App. Phys. **8**, 135 (1937).

viscosity $= b/a$ poises." In order to evaluate m and f from penetration measurements Thelen allows the needle to sink into the material for a series of successive time intervals. For each time interval he calculates a as the additional volume submerged and b as the weight of the descending part of the instrument divided by the total average surface area of the needle submerged during that time interval. By plotting the values of a *versus* b, Thelen found straight line relationships for all asphalts examined. The intersections of the straight lines with the b axis furnished the yield values f for each asphalt. This in turn made it possible to calculate m. One of the asphalts examined (127 penetration, 100 grams, 5 sec. at 25°C) showed a yield value of 0. Thelen calculated its viscosity from the ratio of b/a and obtained an average value of 2.97×10^8 poises. If the viscosity is calculated for the same material by the Saal formula a value of 4.46×10^6 poises is obtained.

Obviously the discrepancy is caused by an error of definition. Thelen assumes the ratio of b/a or the ratio of shearing force per unit area to *volume of flow* to be equivalent to viscosity in poises whereas the coefficient of viscosity is actually defined as the ratio of shearing force per unit area to the *rate of shear*. The ratio b/a has the dimensions $(M \times L^{-4} \times T^{-1})$, whereas viscosity should have the dimensions $(M \times L^{-1} \times T^{-1})$.[6]

Thelen's calculations are affected to a minor extent by an error in physical dimensions of the A.S.T.M. standard needle. He states that the needle has a tip which is the frustrum of a cone whose altitude is 0.43 cm, whose smaller base *radius* is 0.015 cm and whose larger base radius is 0.05 cm. According to A.S.T.M. Standard Test Method D 5–25, the smaller base *diameter* is 0.015 cm. The height of the frustrum is not specified, but can be calculated from the two base diameters and the specified taper of the cone. This height, using base diameters of 0.10 and 0.015 cm is 0.54 cm instead of the 0.43 cm given by Thelen.

From the results of Thelen's experimental procedure the apparent viscosities of the materials tested can be approximated in the following manner:

If the resistance is neglected, which in the descent of the penetrometer needle is caused by the friction between its blunt end and the fluid, and if the needle is permitted to sink at a location close to the axis of the sample container, then the test conditions may be compared with those prevailing in the determination of viscosity by the method of axial displacement of concentric vertical cylinders.[7] This is the case particularly if the penetration test is extended to include a series of measurements for successive time intervals.

The material under test is contained between the outer cylinder of the container and the inner cylinder represented by the shank of the penetrometer needle. Under the load of the penetrometer head the inner cylinder (needle) is permitted to drop. Provided measurements are taken in a region sufficiently far from the bottom of the container, the velocity of the descending inner cylinder (needle) is a direct measure of the apparent viscosity.

The differential equation for these conditions is:[8]

$$W/2\pi rL = -\eta dv/dr,$$

where W is the load in dynes, L the total length of the needle submerged in centimeters and η the viscosity in poises. Integrating for the boundary conditions, r_t = radius of container, v_t = velocity at the surface of the container = 0 and for r_n = radius of needle, v = velocity of the needle we obtain:

$$\eta = W/(2\pi Lv) \times \log_e (r_t/r_n).$$

The container specified by the A.S.T.M. Standard Test Method D 5–25 has a radius of 2.75 cm, the needle of 0.05 cm. The load W is 100 grams which is equivalent to 98,100 dynes. Substituting these values we have

$$\eta = 62{,}600/Lv.$$

L can be calculated as the average depth of penetration or $\frac{1}{2}(P_f + P_i)/100$, where P_f and P_i are the final and initial penetration readings in decimillimeters. They are divided by 100 to obtain L in centimeters. However, this expression for L assumes the needle to be a plain cylindrical

[6] Bingham, *Fluidity and Plasticity* (McGraw-Hill, 1922).

[7] M. Segel, Physik. Zeits. **4**, 493 (1903); A Pochettino, Nuovo Cimento **8**, 77 (1914).

[8] Hatschek, *Viscosity of Liquids* (G. Bell and Sons, London, 1928), p. 184.

TABLE I.

Total Time Sec.	Total Pen. Decimillim.	P_f+P_i-46 Decimillim.	P_f-P_i Decimillim.	Viscosity Poises
5	127	—	—	—
10	176	257	49	496,000
15	214	344	38	478,000
20	245	413	31	488,000
25	274	473	29	456,000
30	298	526	24	495,000
			Average	483,000

shank of constant radius. Since the needle has a conical section, a correction is necessary.

It can be seen from the differential equation that L enters the expression $W/2\pi rL$ as a factor determining the area which absorbs the shearing force P. Since the surface area of the conical section of the needle is considerably smaller than the area of an equivalent length of the cylindrical shank, the value of 0.23 cm was subtracted from all calculated values of L. 0.23 cm is the difference between the height of the cone specified by the A.S.T.M. for the penetration needle (having a lateral surface area of 0.098 cm²) and a cylinder whose radius is 0.05 cm and whose lateral surface area is also 0.098 cm².

The velocity of the needle can be calculated as the ratio of the depth penetrated to the time interval in seconds or $(P_f-P_i)/(100\Delta t)$ plus the velocity of the upward flow of the material under test caused by its displacement by the needle. Hence

$$v=\frac{P_f-P_i}{100\Delta t}+(0.05)^2\pi\frac{P_f-P_i}{100\Delta t}\times\frac{1}{\pi r_t^2},$$

where r_t = radius of the container = 2.75 cm, or

$$v=((P_f-P_i)/100\Delta t)\times(1+0.0025/7.56).$$

Compared to unity the value of the quotient 0.0025/7.56 is so small that it can be neglected.

Substituting the values for L and v, the formula for the viscosity in poises can now be written

$$\eta=\frac{62{,}600\times\Delta t}{(\frac{1}{2}(P_f+P_i)/100-23/100)\times(P_f-P_i)/100}$$

or

$$\eta=\frac{1.25\times10^9}{(P_f+P_i-46)\times(P_f-P_i)}\times\Delta t. \qquad (1)$$

It is of interest to note that the type of the equation corresponds closely to the empirical

TABLE II.

Needle No. 1

Total Time Sec.	Total Pen. Decimillim.	P_f+P_i-46 Decimillim.	P_f-P_i Decimillim.	Viscosity Poises
5	145.5	—	—	—
10	200.0	299.5	54.5	383,000
15	243.3	397.3	43.3	363,000
20	277.5	474.8	34.2	385,000
25	307.0	538.5	29.5	393,000
			Average	381,000

Needle No. 2

5	143	—	—	—
10	195.5	292.5	52.5	307,000
15	239.5	389.0	44.0	365,000
20	273.3	466.8	33.8	396,000
25	304.8	532.1	31.5	373,000
			Average	385,000

Saal formula. This becomes apparent particularly if the conditions for the initial penetration readings are fulfilled, namely $P_i=0$ and $t=5$. Then

$$\eta=\frac{6.25\times10^9}{(\text{penetr.})^2-46\times\text{penetration}}.$$

That the numerical constants do not coincide with those of the Saal formula is to be expected because formula (1) was developed for the cylindrical shank of the needle and not for the conical portion which in the initial reading is of primary importance.

At best formula (1) is an approximation. The calculated values for η should be high since the effect of the blunt tip of the needle is neglected. In order to minimize the error introduced by assuming the needle to be a cylinder the formula should not be used for penetration readings below 100 decimillimeters. Furthermore, during its descent the needle is often only partially wetted by the material under test. Under such conditions the surface of the material is pulled down in funnel shape, thereby obviating the assumptions underlying the formula.

In spite of these limitations it is surprising to find how closely the calculated viscosities check the values obtained from the Saal formula in the case of viscous fluids. As an illustration Thelen's[5] Table II was recalculated (Table I) according to formula (1) to obtain viscosities in poises.

If the viscosity of the material is calculated from the Saal formula the following value is obtained:

$$\eta = 5.13 \times 10^9 / 127^{1.93} = 446{,}500 \text{ poises.}$$

Further to check the validity of the formula a coal tar pitch (softening point ring-and-ball 38.2°C) was tested with the penetration equipment at 25°C. The results given in Table II were obtained.

The viscosity of the pitch was also determined at 25°C by a capillary rise viscometer.[9] Two determinations were made which gave the following results:

$$\eta = 378{,}000 \text{ poises,}$$
$$\eta = 383{,}000 \text{ poises.}$$

When calculated from the Saal formula the viscosity becomes:

$$\eta = 5.13 \times 10^9 / 143^{1.93} = 355{,}000 \text{ poises.}$$

When the limitations of the method are considered, the agreement of the values within less than 10 percent is remarkable. The constancy of the viscosity values calculated from successive penetration intervals indicates that the analysis shown is valid for those Newtonian liquids which wet the penetration needle to the full extent of submersion.

[9] E. O. Rhodes, E. W. Volkmann and C. T. Barker, Engineering News-Record, Nov. 21 (1935).

Fundamental Mechanisms Which Determine the Starting Potentials of the Low Pressure Corona Discharge

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THE variation of the starting potential Vs of the corona discharge in a concentric cylindrical condenser with pressure shows the following behavior for positive and negative corona wire. At pressures near the minimum of the curve in all gases the value of $Vs-$ for the negative wire is lower than $Vs+$ for the positive wire.[1-3] In mixed or impure gases as pressures increase above some 20 to 60 mm pressure the value of $Vs+$ falls below $Vs-$. In *pure* inert gases and pure molecular gases the value of $Vs-$ is always less than $Vs+$.[13] Penning[3] has succeeded in showing that the lowering in He and Ne with Ar and Hg as impurities in amounts as small as 10^{-3} percent, can be ascribed to metastable atoms. The following theoretical treatment of the problem is applicable to all the cases.

Townsend's criterion for sparking is applicable to the case of the corona. In a sufficiently accurate form it reads $\alpha/\beta = e^{\int_a^r \alpha dx}$.[4, 5] Here α is the number of electrons produced by collision per cm advance in the field direction by an electron. The quantity β in Townsend's theory represents a similar quantity produced by positive ion impact in the gas. It will be reinterpreted. In the

[1] L. G. H. Huxley, Phil. Mag. **5**, 721 (1928); **10**, 183 (1930); J. H. Bruce, Phil. Mag. **10**, 476 (1930).
[2] H. F. Boulind, Phil. Mag. **18**, 909 (1934).
[3] F. M. Penning, Phil. Mag. **11**, 979 (1931).
[4] L. B. Loeb, Rev. Mod. Phys. **8**, 267 (1936).
[5] V. N. Kapzov, Physik. Zeits. Sowjetunion **11**, 95 (1937).

TABLE I.

Mechanism		+Wire Corona		−Wire Corona	
		Low Pressure	High Pressure	Low Pressure	High Pressure
Pure Gas	$(\theta-K)\eta$	fairly low	low	—	—
	$K\mu$	—	—	—	—
	$M\epsilon$	—	—	—	—
	γ	low	low	high	fairly low
	Vs	4	12	3	9
Impure Gas No Metastables	$(\theta-K)\eta$	fairly low	low	—	—
	$K\mu$	low	fairly high	—	—
	$M\epsilon$	—	—	—	—
	γ	low	low	high	fairly low
	Vs	4	7	3	9
Impure Gas Metastables	$(\theta-K)\eta$	fairly low	low	—	—
	$K\mu$	low	fairly low	—	—
	$M\epsilon$	low	high	—	fairly low
	γ	low	low	high	fairly low
	Vs	4	5	3	7

divergent field about a corona wire the exponent which in uniform fields is $\alpha\delta$ must be replaced by $\int_a^r \alpha dx$, where a is the radius of the wire and r is a radial distance from the axis where the field is no longer able to give α an appreciable value. Both α and the quantities which replace β are functions of field strength X and pressure p.

To understand the changes in $Vs+$ and $Vs-$ we must replace β by the two expressions below for positive and negative wires.[4] For the positive wire corona, outer cylinder negative

$$\beta=(\theta-K)\eta+K\mu+M\epsilon+\alpha\gamma.$$

For the negative wire corona outer cylinder positive

$$\beta=(\theta-K)\eta g+K\mu\gamma+M\epsilon\gamma+\alpha\gamma.$$

The symbols have the following meaning.

γ is the number of electrons knocked out of the cathode per positive ion striking it. It is very effective at high X/p.

M is the number of metastable atoms formed per cm of electron path in the field direction. (These will be formed only in certain gases, e.g., the inert gases and Hg.)

ϵ is the fraction of metastables that ionize foreign molecules *in the gas*. (Metastable atoms will usually not reach the cathode in any quantity and the electrons created when they do are only partially available so that this action can be omitted.)

θ is the total number of photons capable of ionizing photoelectrically in the gas and at the cathode created per cm path of an electron in the field direction.

K is the number of these photons that are absorbed *in* the gas.

μ is the fraction of these photons absorbed which ionize *foreign* molecules in the gas.

η is the fraction of the $(\theta-K)$ photons striking the cathode which liberate electrons.

In the case of the positive wire the large negative cylinder will insure the liberation of almost all $(\theta-K)\eta$ electrons by photons.

In the case of the negative wire corona the geometry of the system reduces this action by a fraction g which is *very* small.

Since at higher pressures in most negative wire coronas r is small compared to the cylinder radius, most photon and metastable action in the gas will take place where ionization by the electrons no longer occurs. Hence this action *only* contributes *positive* ions to the active region and these only produce $\gamma M\epsilon$ or $\gamma\mu K$ electrons *at* the cathode.

From the sparking equation it is seen that Vs will be the lower the larger the value of β or the smaller α/β for α will therefore not need to be so high in the exponent and thus X/p and Vs can be lower. Since all the terms in the expressions for β vary differently with X/p, and p (absorption by the gas), one can see that the values of Vs under different conditions can be quite different. The behavior to be expected can best be summarized by means of Table I. This gives the character of the gas in the left-hand column. The other columns indicate the status of the various portions of β active for + and − wire coronas at low and high pressure on a scale, low, fairly low, fairly high and high, as well as the observed resultant effects on Vs on a rough relative numerical scale. Where mechanisms are inactive or very weak, as with $K\mu$ on $M\epsilon$ in pure gases at all pressures and $(\theta-K)\eta g$ in the negative wire they are omitted.

This indicates that for pure gases $Vs+$ should always be higher than $Vs-$ and that probably $Vs+$ and $Vs-$ are high compared to the values for impure gases below. In the case of impure gases $Vs+$ is low at higher pressures relative to $Vs-$. The same holds in the case of metastable atoms, although in one case the effect is probably photoelectric while in the other it is an effect of metastables. These latter in fact produce the most striking lowering of any observed.

Until consistent data are obtained for these corona discharges under the different conditions listed, no attempt at evaluating the efficiencies is warranted. Once adequate data are on hand the verification of the hypotheses indicated and the evaluation of the quantities should be possible.

The Effects of Elastic Stretch on the Infrared Spectrum of Rubber

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The absorption spectrum of stretched rubber has been studied in the region between 2μ and 8μ. In the case of unilateral stretch transmission measurements indicate that the absorption bands near 3.3μ and 7μ become broader with increasing stretch while the general background absorption becomes more pronounced. Radial stretch was found to produce similar effects in the 3.3μ and 7μ regions while the bands near 6μ became less intense for both unilateral and radial stretch. In the spectrum of rubber stretched radially to approximately twelve times its original area a band was observed near 4.8μ in a region where there is no intense absorption in the unstretched material. Since both absorption and reflection are involved in transmission measurements, it was necessary to determine reflection and extinction coefficients. The results indicate that the reflection coefficient diminishes and the extinction coefficient increases with increasing stretch. The observed variations in the extinction coefficients are of greater magnitude than those to be expected from the known density changes which accompany stretching.

PREVIOUS studies of the infrared absorption of rubber have been made by Stair and Coblentz[1] and by Williams.[2] Stair and Coblentz observed a small band at 6μ and an intense band near 12μ in addition to the usual hydrocarbon bands at 3.4μ, 7.0μ, and 7.3μ. An interesting study of the effects of aging (oxidation) was carried out by these authors and it was found that marked increases in absorption occurred at 2.8μ, at 6.0μ, and in the region between 7μ and 12μ. Williams obtained transmission data for several types of latex rubber and compared the spectra of these materials with those of related hydrocarbons such as isoprene and styrene. It was found that the small absorption band observed at 6μ by Stair and Coblentz was actually a complex band having several maxima. The results obtained were in fair agreement with the Raman data obtained by Gehman and Osterhof[3] in their studies of solutions of rubber compounds, although the Raman studies revealed the presence of a number of minor frequencies which did not appear in the infrared work.

It has been suggested by a number of writers that the mechanism of elastic stretch is intimately connected with the structure of the rubber molecule, and a theory has been developed by Mack[4] which accounts for stretch and retraction in terms of a rotation about single bonds in the isoprene polymer. That profound changes take place in the structure of rubber when stretched has been revealed by x-ray studies,[5] which show that the diffraction patterns of unstretched rubber consist of the diffuse bands characteristic of liquids, while the patterns of stretched rubber are well defined as in the case of crystalline substances. Other evidences of radical changes in structure accompanying stretch are the variations in optical properties which occur.[6] It was suggested that further infrared studies might be of value in obtaining additional information concerning the mechanism of stretch. Hence it was decided to obtain transmission curves for rubber under different conditions of stretch in an effort to detect any changes that might occur.

The spectrometer used in the present work, a prism instrument of the minimum deviation type, was designed by the authors and constructed in the local Drake laboratory shop. The mirrors, of focal length 230 mm, are 40 mm in diameter. The rocksalt prism, obtained from Kipp and Zonen, has a refractive angle of 60° and refracting faces 40 mm by 72 mm. In order to protect the prism from moisture, all but the refracting faces were covered with a thick layer

[1] R. Stair and W. W. Coblentz, Nat. Bur. Stand. J. Research **15**, 295 (1935).
[2] D. Williams, Physics **7**, 399 (1936).
[3] S. D. Gehman and H. J. Osterhof, J. Am. Chem. Soc. **58**, 215 (1936).
[4] E. Mack, J. Am. Chem. Soc. **56**, 2757 (1934).
[5] For summaries of extensive x-ray work, see G. S. Whitby, J. Phys. Chem. **36**, 198 (1932); M. F. Acken, W. E. Singer, W. P. Davey, Ind. Eng. Chem. **24**, 54 (1932); T. R. Griffith, Can. J. Research **10**, 486 (1934); E. A. Hauser, *Latex* (Chemical Catalog Co., 1930), pp. 154–160.
[6] R. B. Carleton, Rev. Sci. Inst. **5**, 30 (1934).

of a water-proof cement while these were lacquered with an extremely thin layer of pyroxylin in amyl acetate. A Kipp and Zonen compensated thermopile of 18 junctions used as a radiation receiver was connected to a Leeds and Northrup galvanometer of sensitivity $0.01\mu V$/mm for the scale distances used. The extreme steadiness of the zero point made it possible to use small deflections since the shift of zero reading was seldom greater than one or two millimeters per hour. The air deflections varied from 12.0 cm near 3μ to 2.8 cm in the water vapor band at 6μ. The actual slit widths used were: 0.005 cm between 2μ and 4.5μ, 0.010 cm, between 4.5μ and 6.5μ, and 0.015 cm between 6.5μ and 8.0μ. In the earlier part of the work an optical relay system using a photronic cell was employed, but mechanical vibrations in the building made it necessary to discard the amplifier. In taking the transmission data, about 16 readings per μ were taken in the 3μ region and 24 per μ at 7μ. After the spectrum had been mapped carefully, fewer readings were taken, but these were concentrated in regions of particular interest. In making the wave-length calibration curve Paschen's values[7] for the indices of refraction were used, the theoretical curve being checked experimentally by means of the sodium D lines, the water vapor bands, the carbon dioxide bands, and the bands of liquid water, alcohol, and benzene. There are but slight discrepancies between band positions as determined in this manner and those obtained in previous work[2] by means of the Hilger calibrated drum. There is close agreement between the present results and those obtained by Stair and Coblentz.[1]

A wide range of materials was studied in the present investigation, and the writers are especially grateful to Dr. S. D. Gehman, Dr. R. H. Gerke, and Dr. Lewis Larrick for their kind cooperation in furnishing samples. The materials which had of necessity to be reasonably clear and free from surface irregularities ranged from uncured latex rubber to vulcanized rubber with sulphur content as high as 10 parts of sulphur to 100 parts of rubber hydrocarbon. As far as the method of cure is concerned, it was found that the effects about to be described are to a large extent independent of the cure except that the compounds containing high sulphur concentrations are unable to withstand sufficient stretching to make the results significant. The material found best suited for use in this study was a type of sheet latex rubber containing about one percent of zinc oxide and stearic acid. In all, the complete spectra from 2μ to 8μ were obtained for some fifty-five samples of rubber under different conditions of stretch, while transmission data in regions of special interest were obtained in about thirty other cases. To provide unilateral stretch, flat brass plates 10 cm apart were fastened to an ordinary absorption cell holder and clamped the rubber firmly after the desired elongation had been obtained. Layers of felt between the clamps and rubber provided better contact and prevented slipping while the observations were being made. The effects of local strains due to the clamps were minimized by allowing the radiation to pass through the middle of the sample. The measurements of the lengths were made with an ordinary centimeter scale; the large sizes of the samples used made such a method of measurement sufficiently accurate.

Several mechanical devices for producing radial stretch were designed and tested. However, it was found that the most satisfactory results were obtained by stretching the sheet rubber over a wide metal ring of large diameter and holding it in place by means of a strong rubber band. A small circle was printed on the unstretched rubber, and the sheet was stretched until this circle mapped into a larger concentric circle of the desired size. In cases where extremely large increases in area were desired, it was found necessary to use several successive reference circles, since the width of the lines defining the original circle became too wide to permit accurate measurements. In all cases care was taken to prevent the appearance of regions of local strain in the samples. Measurements of thickness were made with a micrometer gauge and readings were taken when the pressure on the sample had reached a definite value determined by the ratchet. Repeated tests on the same sample taken on different days indicate that the readings taken in this manner could be repeated satisfactorily. On any one sample a number of determinations

[7] C. Schaefer and F. Matossi, *Das Ultrarote Spektrum* (Springer, Berlin, 1930), p. 46.

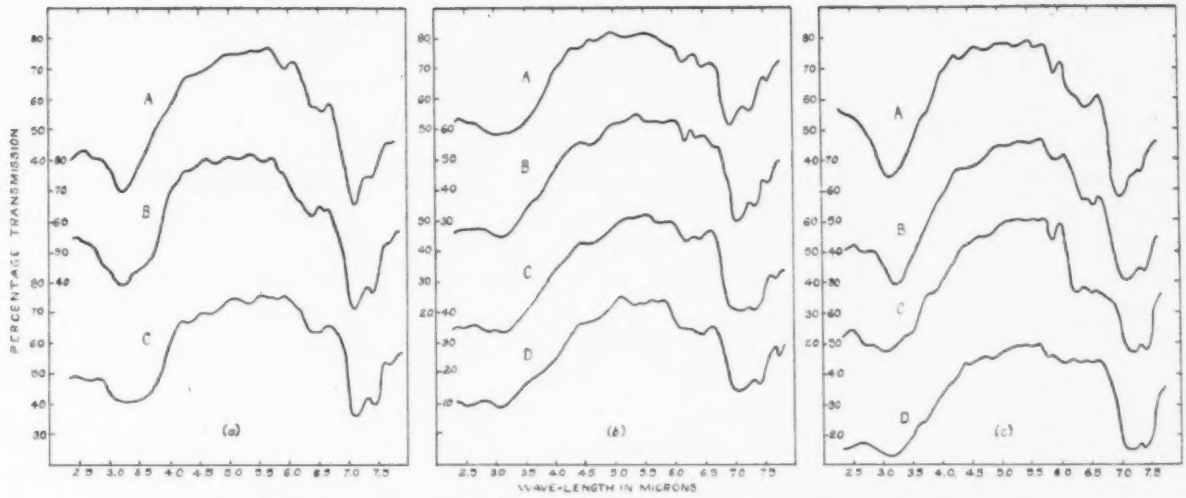

FIG. 1. The transmission of rubber under various conditions of unilateral stretch.

of thickness were made and the average used.

In Fig. 1 are indicated the results obtained for unilateral stretch. The curves in Fig. 1 (*a*) represent the transmission of a single layer under different tensions. Curve *A* shows the transmission of an unstretched layer 0.045 mm in thickness. It will be noted that in this curve there are regions of strong absorption with maxima at 3.26μ, 7.10μ, and 7.35μ, while weaker bands appear in the 6μ region. It has been found that in different samples of unstretched rubber the exact positions of the maxima vary slightly, the exact position depending in part on the thickness and in part on the condition of the surfaces. In unstretched materials the positions of the apparent maxima vary from 3.2μ to 3.4μ, 6.9μ to 7.1μ, and 7.3μ to 7.4μ, respectively. It will be noted that two less intense absorption maxima appear at 5.9μ and at 6.5μ. These less intense bands appear in the regions where one would expect the fundamental linear vibrations of C=C and the first harmonics of C−C to produce absorption. The complex absorption in this region is radically affected by stretching. However, owing to the relatively low resolution and the small galvanometer deflections obtainable in this region, little definite information could be gained on this subject. It may be well to point out at this point that there are a large number of minor absorption bands in the rubber spectrum between 4μ and 6μ. These bands, which appear as small depressions of five or six percent in the transmission curve, were thought at first to arise from interference effects such as those described by Ellis in his studies of Cellophane.[8] However, since the positions of these minor bands remain approximately the same when different thicknesses are studied, the writers are inclined to believe that they are true absorption bands and are possibly harmonics of bands appearing at longer wave-lengths. Evidences for absorption of this type were also found in previous studies.[2]

Curves *B* and *C* of Fig. 1 (*a*) represent the transmission of the same sample after it had been stretched unilaterally until the thicknesses of the absorbing layers were 0.030 mm and 0.023 mm, respectively. Several marked changes are apparent. The 3.25μ band becomes broader and its center of absorption is shifted to longer wave-lengths with increasing stretch. The 7μ absorption bands also become broader, while the 7.35μ band becomes more intense as compared with the 7.1μ band. However, the most interesting point observed is that the general absorption is appreciably greater in the case of the stretched samples. Thus, we find the transmission at 3.25μ and at 7μ in curve *C* only ten percent higher than in curve *A*, while the general absorption at 5μ is actually greater for curve *C*. The fact that the thickness of the sample whose transmission is indicated in curve *C* is actually only half that of the sample used for curve *A* would lead one to expect changes greater than those observed. It is evident that the absorbing properties of

[8] J. W. Ellis, J. Opt. Soc. Am. **23**, 88 (1933).

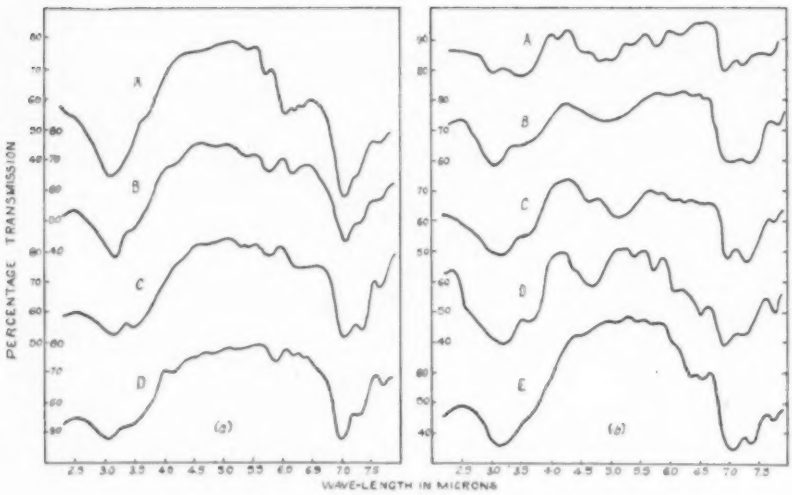

FIG. 2. The transmission of radially stretched rubber.

rubber become greater when the material is under tension. In the 6μ region the intensity diminishes appreciably with increasing stretch.

The possibility that the observed effects might be only apparent, arising from variations in thickness alone, led to the study of a number of different thicknesses of sheet rubber experiencing the same percentage elongation. Some of the results are indicated in Fig. 1 (*b*), where the curves *A*, *B*, *C*, and *D* represent transmission data for thicknesses of 0.014 mm, 0.030 mm, 0.045 mm, and 0.063 mm, respectively. All the samples used in obtaining the curves shown in this part of the figure were experiencing an elongation of approximately three hundred percent. It will be noted that the bands at 3μ and 7μ become broader with increasing thickness, as one would expect. The observed increase in the intensities of the bands and of the general absorption is to be expected. When these curves are compared with the transmissions of the same thicknesses of unstretched rubber, it is found that the absorption is greater in the case of the stretched samples.

Comparisons of the transmission of layers of equal thickness (0.045 mm) under different conditions of stretch are given in Fig. 1 (*c*). In the curves *A* and *B* are shown the spectra of samples under zero tension before and after stretching, a few minor variations appearing at 3.2μ and near 6μ. Curves *C* and *D* represent the transmission of samples having the same thickness when experiencing one and three hundred percent elongations, respectively. These curves make even more pronounced the general effects noted in connection with the curves of Fig. 1 (*a*).

The transmission spectra of rubber experiencing radial stretch are shown in Fig. 2 (*a*). Curve *A* represents the transmission of the unstretched layer 0.045 mm in thickness. Curves *B*, *C*, and *D* represent the spectra of the same sample after the area had been increased one hundred, two hundred, and three hundred percent, respectively, by radial stretching. As in the case of unilateral stretch, the general absorption becomes greater and the major bands become broader with increasing stretch. One point of special note is the manner in which the 3.2μ region of absorption becomes broader as elongation increases. A second maximum appears near 3.5μ and becomes more pronounced as stretching continues, while the maximum originally present at 3.2μ is apparently shifted to slightly shorter wave-lengths. If stretching is continued until the sample is seven or eight times the original area, the 3.5μ depression often becomes even more pronounced than the one at 3.2μ. In the case of radial stretch the small bands appearing in the 6μ region become less intense than those in the spectra of unstretched and unilaterally stretched rubber and are completely absent in some samples. There are small shifts in position of the maxima in the 7μ region, but these slight shifts can scarcely be considered of great significance, since there is considerable overlapping of the principal bands in this region.

It was observed that when samples of rubber were stretched radially to the limit—eleven to thirteen times the original area in most cases studied—an intense absorption band appeared near 4.8μ, a spectral region in which there is no strong absorption in unstretched rubber. Spectra of stretched specimens showing this band are given in Fig. 2 (*b*). In curve *A* this band appears at 4.7μ and is nearly as intense as the bands in the 3μ and 7μ regions. In curve *A* the 3.5μ ab-

sorption is more intense than the band appearing at 3.15μ. In curves B and C the additional band appears near 4.8μ. The center of the band appearing in curve B lies at 4.85μ, while in curve C the band appears as a double band with one maximum at 4.65μ and the second at 5.10μ. The rubber used in obtaining these transmission curves was a cured type containing about one percent of zinc oxide and stearic acid and one percent of sulphur. It was suggested that the band appearing near 4.8μ might arise from a sulphur-carbon vibration, since a band appears at this position in the spectrum of carbon disulphide.[9] In order to test this point sheets of uncured latex rubber were stretched radially to the limit—about seven or eight times the original area—and their transmissions measured. Stretching uncured rubber radially to this degree without tearing was rather difficult. Data had to be taken immediately after the specimen was prepared since flow was quite rapid in most cases. The results obtained with one sample are shown in curve D, in which an intense absorption band appears at 4.7μ. The band was obtained for several uncured samples, but that shown in curve C is more intense than in most of the others. It was found that after samples had been stretched for several hours the natural flow was sufficient to relieve the tension and the effects of stretch disappeared from the spectrum. The final curve in the figure, curve E, is the transmission curve of an unstretched layer of rubber 0.045 mm in thickness and is included for purposes of comparison.

In determining the transmission of a substance like rubber a number of effects are involved. As in the case of any transmission spectrum, the selective reflection and the selective absorption are the predominant phenomena concerned. However, one must consider other effects such as diffuse reflection, scattering by surface irregularities, and also scattering and reflection by particles within the body of the material being studied. In order to determine the causes of the changes in the rubber spectrum which accompany stretch, it is necessary to gain an idea of the relative variations in these effects. The surface phenomena, including general, diffuse, and selective reflection will enter into the transmission equation in the form of a coefficient, since their magnitudes in no way depend upon the thickness of the sample under consideration. The true absorption and the body scattering, however, are dependent on the thickness of the sample and hence appear in the exponential factor of the transmission relation. Thus, we may write the orinary equation in the form:

$$I=(1-\rho)I_0e^{-\alpha t},$$

where I represents the measured intensity of the transmitted radiation, I_0 the intensity of the incident radiation, and t the thickness of the absorbing layer. The coefficient ρ is the term arising from the surface effects and the term α in the exponent is a measure of the true absorption plus body scattering.

By measuring the thicknesses t_1 and t_2 and the intensities I_1 and I_2 of the radiation transmitted by two different specimens under similar conditions, it is possible to gain an idea of the relative contributions of the surface and body phenomena by solving Eqs. (1) and (2) for ρ and α.

$$I_1=(1-\rho)I_0e^{-\alpha t_1}, \quad (1)$$

$$I_2=(1-\rho)I_0e^{-\alpha t_2}. \quad (2)$$

Involved in this procedure are difficulties which are immediately apparent. One of these lies in the inaccuracies involved in determining the thickness of a substance having properties like those of rubber; the methods described above and employed in the present study are open to criticism. A more serious difficulty arises from the questionable assumption that the term ρ which involves surface irregularities is the same even for samples taken from the same sheet, since there is no method of estimating the variations introduced in the interdependent terms ρ and α.

Measurements were made on a number of samples which enabled α and ρ to be determined as a function of percentage stretch. In Table I are given the values of these constants obtained in the representative spectral regions: 3.35μ, 5.5μ, 7.1μ, and 7.35μ. It will be noted that in every spectral region considered, the body coefficient α increases with increasing stretch, while the surface factor ρ decreases with stretch. These changes are similar for radial and uni-

[9] J. A. Sanderson, Phys. Rev. **50**, 209 (1936).

TABLE I.*

A. UNILATERAL STRETCH

PERCENT STRETCH	3.3μ		5.5μ	
	α	ρ	α	ρ
000	10.3	0.22	0.5	0.21
100	17.7	0.29	2.0	0.18
200	20.8	0.27	6.0	0.09
300	36.2	0.11	11.5	0.05
400	34.0	0.14	12.2	0.03
500	27.0	0.11	10.0	0.02
600	26.0	0.13	10.0	0.03
	7μ		7.1μ	
	α	ρ	α	ρ
000	10.0	0.51	7.4	0.66
100	23.1	0.29	28.2	0.31
200	27.5	0.25	25.1	0.20
300	36.3	0.17	25.0	0.19
400	40.0	0.20	34.0	0.15
500	24.0	0.24	20.0	0.26
600	32.0	0.16	30.2	0.18

B. RADIAL STRETCH

PERCENT STRETCH	3.25μ		5.5μ	
	α	ρ	α	ρ
000	10.3	0.54	4.5	0.10
100	12.3	0.48	5.8	0.12
200	18.0	0.40	9.0	0.08
300	13.7	0.35	14.5	0.07
400	23.3	0.26	11.0	0.07
500	42.2	0.14	13.5	0.05
600	30.0	0.23	10.0	0.07
	7.1μ		7.3μ	
	α	ρ	α	ρ
000	7.9	0.59	6.0	0.64
100	8.2	0.58	23.2	0.36
200	18.0	0.40	37.2	0.19
300	23.7	0.29	35.0	0.20
400	30.0	0.23	30.0	0.22
500	36.0	0.23	29.9	0.25
600	30.0	0.30	33.3	0.21

* The values given in the table are accurate to approximately ten percent.

lateral stretch. Owing to the variations introduced by differences in the surface conditions of any one pair of samples, the exact values of ρ and α vary within certain limits even for samples taken from the same sheet of rubber, but the changes with stretch are in the same direction for all specimens considered and are indicative of a definite trend which shows the body coefficient for six hundred percent stretch to be roughly three times as great as that for unstretched rubber. The observed changes in the body coefficient with stretch are much greater than those predicted on the basis of the known variations of density.[10] The accuracies of α and ρ given in Table I are based on the errors involved in the determinations of transmission and thickness and should not be taken to indicate the probable error as obtained from a large number of observations. The data shown are the values as obtained from two representative samples under various tensions.

In view of the observed doubly refracting properties of stretched rubber,[6] it was suggested that these properties might in some way account for the observed changes in the body coefficient. Although the incident light experiences only one reflection before reaching the absorption cell position, the radiation undergoes five reflections in passing through the spectrometer and hence is slightly polarized by the time it reaches the thermopile. In obtaining the data for the unilaterally stretched rubber, every sample was placed in the light beam with the direction of stretch the same. However, tests showed no appreciable change in transmission when the direction of stretch was varied. Therefore it is doubtful that the observed changes in body coefficient can be attributed directly to double refraction.

Although a purely theoretical interpretation of the vibration spectrum of a highly polymerized material like rubber is impossible, it may nevertheless be possible to draw some inferences on the basis of the empirical relationships developed by a number of investigators.[11] Thus, since bands have been found in the same positions in the spectra of large numbers of organic compounds, it has been possible to attribute the 3.35μ bands to a linear vibration of CH bonds and the 7μ bands to deformation frequencies of CH_2 and CH_3 groups. Of course, all the bands arise from normal vibrations of whole molecules, but their frequencies are largely determined by the natural vibrations of certain groups and it has become customary to speak of the frequencies involved

[10] W. L. Holt and A. T. McPherson, Nat. Bur. Stand. J. Research **17**, 657 (1936).
[11] R. B. Barnes, Rev. Sci. Inst. **7**, 265 (1936).

as though they actually arose from particular groups. Thus, one may consider the broadening of the 3μ band with increasing unilateral stretch as being the result of new constraints placed directly on the CH bonds or as being the effect of other radical changes in the rubber structure which cause variations in the normal frequencies of the molecules. Since the shift of the band position is toward longer wave-lengths, it is apparent that the stresses are such as to cause lower vibrational frequencies to be assumed by a large number of the absorption units present. The broadening of the 7μ region of absorption and the relative increase in the intensity of the 7.3μ component in unilaterally stretched samples are further evidence of lower frequencies in the case of stretched rubber. The x-ray work of Hausser and Mark[5] shows that unilaterally stretched rubber gives rise to a spot diffraction pattern superimposed on the amorphous ring characteristic of unstretched rubber. Since the positions of the spots remain unchanged with increasing stretch, it is concluded that they arise from a definite space lattice. The intensity of the spots increases with the tension, while the intensity of the amorphous ring decreases. The conclusion drawn from these x-ray observations is that in the process of stretching there is a gradual transition from a liquid (amorphous) phase to a crystalline phase. From the diffraction patterns Hausser and Mark find evidence of a typical fiber structure. It is probable that the units possessing the lower frequencies observed in the present work are those in the crystalline lattice, since these units are influenced to a greater extent by their immediate neighbors.

In the radial stretch data the variations in the 3.3μ and 7μ bands are similar to the changes accompanying unilateral stretch in that broadening takes place and that the intensity of the bands is greater. However, there is no pronounced shift toward longer wave-lengths in either band. The 3.3μ band, which is double when the material is stretched radially, is different in shape from the band observed in unilaterally stretched rubber. The center of the region of absorption near 7μ remains practically unchanged in position, since the higher frequency component shifts to shorter wave-lengths and the 7.3μ band increases in intensity. As mentioned above, little significance can be attached to the shifts of the maxima of the individual components in this region since overlapping occurs and the shape of the measured transmission curve is hence dependent on thickness. There is, however, ample evidence of changes in the rubber structure which are different from those observed in the case of unilateral stretch. The intensity of the complex absorption near 6μ was noticeably diminished by radial stretch; further study of this region under high dispersion might prove valuable. The appearance of the broad bands near 4.8μ in the spectra of radially stretched samples gives additional evidence of structural change. From the results obtained in the present study it is impossible to ascribe this absorption at 4.8μ in the spectra of radially stretched samples to any definite group. The band was observed in the spectra of a number of specimens of different thicknesses, and its intensity is so great that it is doubtful that it can be attributed to interference effects. Since the x-ray results indicate the existence of a ring structure[5] in radially stretched rubber, it is possible that the 4.8μ band arises from one of the units in this type of lattice. The lattice in radially stretched rubber is markedly different from the fiber structure caused by unilateral stretch.

In ordinary rubber there are two types of hydrocarbons present: the sol or alpha-rubber and the gel or beta-rubber. These hydrocarbons are distinguished by their different solubilities in ether and are thought by most writers to represent different degrees of polymerization of the isoprene units. In the interpretation of the early x-ray results it was suggested that the characteristic crystalline diffraction patterns were caused by the beta component, the relative amount and regularity of arrangement of which was supposed to be increased by stretching. However, when it was discovered later that crystalline patterns could be obtained by stretching pure alpha-rubber, some doubt was cast upon the earlier interpretation. Stair and Coblentz found the spectra of alpha- and beta-rubber identical up to 9μ. Thus, the changes in the rubber spectrum observed in the present investigation offer further evidence that the crystalline component of stretched rubber cannot be identified with beta-rubber.

It was noted above in the discussion of absorp-

tion and reflection effects that the coefficient α, which included the true absorption and body scattering, became larger with increasing stretch and for a stretch of six hundred percent was approximately three times as great as for zero stretch. In order to have a check on the values obtained it was decided to compare the values of the coefficients with the absorption coefficients of other organic compounds. Since the band near 3.3μ is simpler in structure than any of the other characteristic bands observed, it was chosen for comparison with the corresponding bands in the spectra of other unsaturated hydrocarbons. The data of Coblentz[12] were chosen for use in making the comparison, since large numbers of compounds were studied under the same conditions and with the same methods. To have a common basis for comparison, it was necessary to compute the effective absorption coefficients per CH bond in the following manner: If α is the absorption coefficient per centimeter of thickness, we may obtain the absorption per molecule α_M by the relation:

$$\alpha_M = \alpha M/\rho N$$

where M is the molecular weight, ρ the density, and N Avogadro's number. Then, on dividing α_M by the number of CH bonds per molecule, one may obtain the coefficient per CH bond, which we will denote by α_{CH}. In Fig. 3 are shown the results obtained from Coblentz' work on unsaturated hydrocarbons; α_M is plotted as a function of the number of CH bonds per molecule. It will be noted that the points approximate a straight line, the slope of which gives the average value of α_{CH} for the unsaturated hydrocarbons. In Table II are given the values of α_{CH} as obtained for the individual compounds and also the values of the body coefficient per CH bond obtained in the present study of rubber. The fact that the value of the body coefficient for unstretched rubber is in reasonable agreement with the values obtained for other hydrocarbons is an additional check on the accuracy of determinations of thickness made in the present work.[13]

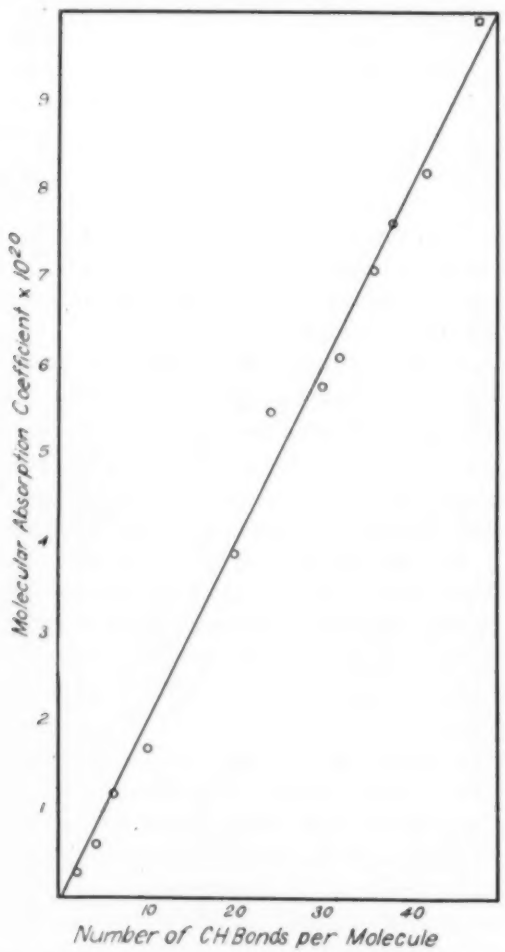

FIG. 3. The absorption coefficient per molecule of various unsaturated hydrocarbons in the region of 3.3μ as a function of the number of CH groups per molecule.

[12] W. W. Coblentz, Carneg. Inst. Pub. No. 35 (1905).

TABLE II.

COMPOUND	STATE	$\alpha_{CH}\times10^{21}$	NOTE
C_2H_2	Gas	1.5	Triple Bond
C_2H_4	Gas	1.6	One Double Bond
$(CH_3)_2O$	Gas	1.9	Methyl Ether
$(C_2H_5)_2O$	Gas	1.7	Ethyl Ether
$C_{10}H_{20}$	Liquid	2.0	One Double Bond
$C_{12}H_{24}$	Liquid	2.3	One Double Bond
$C_{13}H_{30}$	Liquid	1.9	One Double Bond
$C_{16}H_{32}$	Liquid	1.9	One Double Bond
$C_{18}H_{38}$	Liquid	2.1	One Double Bond
$C_{24}H_{48}$	Liquid	2.1	One Double Bond
$C_{19}H_{36}$	Liquid	2.0	One Double Bond
$C_{22}H_{24}$	Liquid	2.0	One Double Bond

RUBBER	PERCENT STRETCH	UNILATERAL $\alpha_{CH}\times10^{21}$	RADIAL $\alpha_{CH}\times10^{21}$
	000	0.9 to 1.8	0.9 to 1.8
	100	2.1 to 2.6	1.5 to 2.1
	200	2.2 to 3.3	1.8 to 2.6
	300	4.1 to 5.2	1.9 to 3.0
	400	4.4 to 5.3	3.0 to 4.0
	500	4.0 to 5.2	4.4 to 5.0
	600	3.9 to 5.2	4.4 to 5.2

[13] The value of M used in the determination of the coefficient for rubber was the value for isoprene. However,

The values of α_{CH} for rubber experiencing a six hundred percent stretch are approximately three times as great as the values for unstretched rubber. There are two possible explanations tenable; the absorption per molecule may actually increase as a result of the stresses applied to the bonds themselves on stretching, or the apparent increase may arise from greater internal scattering caused by the creation of the crystal lattice in the body of the originally amorphous phase. From the results obtained thus far it is impossible to determine which of these effects plays the more important role in producing the observed effects.

The writers wish to express their appreciation to Mr. F. H. Hayes and Mr. H. B. Messec for their aid in the construction of certain parts of the apparatus and to the members of the physics staff for their interest in the work.

the value of α_{CH} would have been unchanged had the value of M for a polymer been used, since the number of CH bonds varies directly with the order of the polymer.

The Viscosity of Raw Rubber

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(Received from the Editor of the Society of Rheology, April 13, 1937)

Eyring's reaction rate theory of the viscosity of simple and of non-Newtonian liquids has been outlined. Mooney's data on the rheology of a sample of raw rubber have been shown to be in agreement with Eyring's theory. The data have been discussed from the viewpoint of the theory, and some conclusions have been drawn concerning the probable mechanism of viscous flow in raw rubber.

INTRODUCTION

EYRING[1] has recently published a theory of the viscosity of both simple and non-Newtonian liquids. This work is based on recent developments in the theory of homogeneous reaction velocities.[2] The latter theory was initiated by the well-known Arrhenius equation for the velocity constant of a reaction:

$$k = Ae^{-B/RT}.$$

Here A and B are constants characteristic of the reaction, R the gas constant, and T the absolute temperature. The constant A depends upon the spatial requirements which must be fulfilled by the reacting molecules. B equals the average energy of the reacting molecules minus the average energy of all the molecules, and is spoken of as the "activation energy" of the reaction. The newer theoretical work has enabled the calculation of both the factor A and the activation energy, using the straightforward methods of statistical mechanics. In the applications of the theory to condensed systems, the molecular force fields are not, in general, sufficiently well known to permit quantitative predictions of reaction velocity. In principle, however, the calculations may be carried through. Since it is not possible to make a detailed application of the theory of reaction rates to problems of viscosity, further outline of this theory will be omitted.

The contribution which Eyring has made to the theory of viscosity lies in his recognition of the fact that in many cases flow takes place by means of activated, that is to say, energy-rich molecules. The phenomenon may therefore be treated by the same methods which have been shown to be successful in describing velocities of chemical processes. Although the foregoing has been recognized with varying degrees of clarity by a number of earlier investigators,[3] Eyring has expressed the relationships in a more concrete

[1] H. Eyring, J. Chem. Phys. **4**, 283 (1936).
[2] H. Eyring, J. Chem. Phys. **3**, 107 (1935); M. G. Evans and M. Polanyi, Trans. Faraday Soc. **21**, 875 (1935); W. F. K. Wynne-Jones and H. Eyring, J. Chem. Phys. **3**, 492 (1935). Cf. also: W. H. Rodebush, J. Chem. Phys. **1**, 440 (1933); V. K. LaMer, ibid. **1**, 289 (1933); O. K. Rice and H. Gershinowitz, ibid. **2**, 853 (1934) and further references cited in the foregoing.
[3] J. M. Burgers, *First Report on Viscosity and Plasticity* (Amsterdam, 1935) chap. II. Cf. also: W. F. Busse and E. Karrer, Kolloid-Z. **65**, 211 (1933).

form and, in addition, has shown how the viscosity depends on shearing stress in certain cases of non-Newtonian fluids.

The discussion proceeds as follows: The average molecule in a liquid is confined by van der Waals forces to a region of low potential energy. When, in the course of statistical fluctuations about this average state, the molecule acquires thermal energy in excess of the average, it may escape from the potential "hole" to an adjacent potential minimum. It should be noted that this picture of the liquid state bears a closer analogy to the situation existing in solids than to that which obtains in the gaseous state. This point of view is well established through a variety of theoretical work. In the case of a liquid which experiences no external unbalanced forces, the jumping of the molecules from one potential minimum to another takes place uniformly in all directions so that there is no net flow. If, however, a shearing stress is applied to the fluid, it has the effect of lowering the activation energy in one direction and increasing it in the reverse direction. In other words, the applied stress pulls the molecules out of the potential holes in one direction, and makes it more difficult for them to jump in the reverse direction. There is, therefore, a net flow of the fluid.

We may calculate the viscosity of the system in the following manner. Consider a fluid confined between two planes, $z=0$ and $z=Z$. The upper plane moves with uniform velocity in the direction of increasing x. We assume that a laminar flow is set up in the fluid. By definition

$$\eta = f/(dV/dz), \tag{1}$$

where η is the viscosity of the fluid, f the shearing stress, and V the velocity of the layer, parallel to the x, y plane, and at a height z. dV/dz may be expressed for our purposes as $\Delta V/\lambda_1$, where λ_1 is the distance between two adjacent layers, and ΔV is the difference in velocity between these two layers. The rate of flow in the forward direction will then equal the fraction of the molecules which are activated, times the frequency with which they jump, times the distance they go in each jump. This is expressed by the following equation:

velocity of forward flow =

$$k_0 \exp\left\{-\frac{E_0-\frac{1}{2}f\lambda_2\lambda_3\lambda}{kT}\right\}\cdot\frac{kT}{h}\cdot\lambda. \tag{2}$$

Here k_0 is the equilibrium constant expressing the number of activated molecules in proportion to the total number of molecules, but neglecting the activation energy. The exponential term takes account of this latter factor. Here E_0 is the depth of the potential hole (the activation energy in the absence of shearing stress) and the quantity $\frac{1}{2}f\lambda_2\lambda_3\lambda$ is the work done by the applied force in assisting the molecule out of the potential hole. λ_2 and λ_3 are the dimensions of the molecule along the X and Y directions respectively. Their product, therefore, gives the cross section on which the applied force acts. k is the Boltzmann constant (gas constant per molecule) and T is the absolute temperature. The fraction kT/h, where h is Planck's constant, expresses the frequency with which the activated molecules jump. λ is the distance each molecule jumps.

Similarly, the rate of flow in the reverse direction may be written:

velocity of backward flow =

$$k_0 \exp\left\{-\frac{E_0+\frac{1}{2}f\lambda_2\lambda_3\lambda}{kT}\right\}\cdot\frac{kT}{h}\cdot\lambda. \tag{2'}$$

Subtracting these, we obtain for the net velocity of the layer under consideration with respect to a layer λ_1 centimeters away,

$$\Delta V = k_0\lambda\frac{kT}{h}e^{-E_0/kT}\cdot 2\sinh\frac{f\lambda_2\lambda_3\lambda}{2kT}. \tag{3}$$

By substitution we obtain the following expression for η:

$$\eta = \tfrac{1}{2}f\frac{\lambda_1}{\lambda}\frac{1}{k_0}\frac{h}{kT}e^{E_0/kT}/\sinh\frac{f\lambda_2\lambda_3\lambda}{2kT}. \tag{4}$$

Eyring has given a brief discussion of the application of this equation to Newtonian liquids. In this case $\frac{1}{2}f\lambda_2\lambda_3\lambda \ll kT$. Expanding the sinh and neglecting all terms of higher power than the first, Eyring finds

$$\eta = \frac{\lambda_1 h}{k_0}\cdot\frac{1}{\lambda_2\lambda_3\lambda^2}e^{E_0/kT}. \tag{4a}$$

He then shows that this expression gives results equivalent to those obtained from the empirical equations of Andrade and of Batschinski when applied to nonassociated liquids. It should be noted that, as must be the case, f does not appear in Eq. (4a). In words: the viscosity of a Newtonian liquid is independent of the shearing stress.

The application of Eq. (4) to non-Newtonian liquids is of importance in the present discussion. Let us consider the case when $\frac{1}{2}f\lambda_2\lambda_3\lambda \gg kT$. Then

$$\sinh \frac{f\lambda_2\lambda_3\lambda}{2kT} \approx \exp \frac{f\lambda_2\lambda_3\lambda}{2kT}.$$

In practice the above approximation is valid if $f\lambda_2\lambda_3\lambda/2kT \geq$ about 1.5. Eq. (4) then becomes

$$\eta = f\frac{\lambda_1}{\lambda}\frac{1}{k_0}\frac{h}{kT}\exp\left\{\frac{E_0 - \frac{1}{2}f\lambda_2\lambda_3\lambda}{kT}\right\}, \qquad (4b)$$

which may be rewritten in the form:

$$\eta = Afe^{(a-bf)/T}. \qquad (5)$$

Here, of course, f does appear in the equation.

There are very few data in the literature of sufficient scope to enable a test of this equation, with the exception of some recently published figures obtained by Mooney.[4] These data were obtained by means of the rheometer. They describe the viscosity of a sample of pale crepe (after milling for 5 minutes) as a function of temperature and shearing stress. The present paper contains a check of Eyring's theory by means of Mooney's data, and an interpretation of the data in terms of the theory.

Procedure

The constants in Eq. (5) necessary to give the best fit with the experimental data were obtained as follows: First the equation was rearranged to the form

$$\log_{10} \eta/f = \log A + (a - bf)/2.3T. \qquad (6)$$

A preliminary plot of $\log \eta/f$ *vs.* $1/T$ was made, and the slope of each line adjusted so as to give an approximately linear relation of slope with shearing stress. The values of the slopes were then plotted against the shearing stress and extrapolated to zero stress. This curve gave the values for a and b. The constant A was obtained from the individual curves of the preliminary plot, neglecting the points corresponding to the lowest and highest values of shearing stress, since it was obvious that the former did not fit the equation, and since the latter were too scattered to be taken into account for the present purpose. It should be mentioned that it is not possible to fit the lowest shearing-stress curve and also those of intermediate stresses by manipulation of the three constants of Eq. (5). The values of these constants for this particular sample are:

$$A = 1.65\times10^{-4},$$
$$a = 5.10\times10^{3},$$
$$b = 1.28\times10^{-5}.$$

The extent of the agreement is shown in Fig. 1 in which $\log \eta/f$ is plotted against $1/T$. The points are Mooney's experimental data and the lines are given by Eq. (5) using the above values for A, a and b.

Discussion

The discrepancies between calculated and observed values are no greater than the possible experimental error (neglecting the curve of lowest shearing stress) with the possible exception of the data for the highest shearing stress. These latter may represent either a permanent change in the rubber, or the limit of the applicability of Eq. (5). Further experimental work will be necessary to settle this point. Discussion of the curve for lowest shearing stress will be postponed for the moment.

Constant b

From Eq. (4a) it is seen that b equals $\lambda_2\lambda_3\lambda/2k$. If we assume that the distance jumped by the molecule is equal to the length of the molecule, $\lambda_2\lambda_3\lambda$ may be expressed as a volume per molecule or mole. This volume is equal to 3.52×10^{-19} cc per "molecule," or 2.13×10^{5} cc per "mole." This assumption is surely not valid in the case of a rubber molecule. It seems much more probable that the distance jumped is of the order of magnitude of a small multiple of the length between two double bonds. If this is the case, the cross section of the moving particle is much

[4] M. Mooney, Physics **7**, 413 (1936).

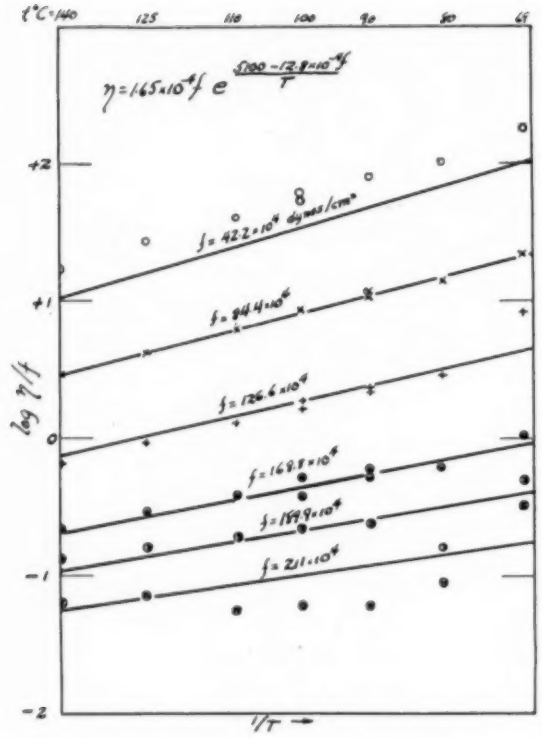

FIG. 1. Plot of $\log \eta/f$ vs. $1/T$ for a sample of pale crepe after milling for 5 minutes.

greater than that of a rubber molecule. It may therefore be concluded that the moving particle in slightly masticated rubber consists of a cluster of hydrocarbon chains rather than an individual molecule.

Constant *a*

Since a has been found to be equal to 5100, E_0 is readily calculated to be 10.2 kcal./"mole." This seems a rather large activation energy to be caused by van der Waals attractions, judging from the temperature coefficient of the viscosity of low molecular liquids. In the present case E_0 is large because of the large size of the moving particle.

Constant *A*

According to the theory of reaction rates this constant is given by the expression

$$A = H(\lambda_1/\lambda)(F_n/F_a^*)(h/kT). \qquad (7)$$

Here H is a "transmission coefficient" expressing the probability that the molecules, being in a state satisfying both energy and spatial requirements will react, that is to say in the present case, jump from the potential minimum. For our purposes this constant may be assumed with considerable certainty to equal unity. λ_1 and λ have been previously defined. F_n and F_a^* represent, respectively, the partition functions of the normal and of the activated molecules. These quantities have been defined and discussed by Fowler.[5] In the Darwin-Fowler statistical theory they play the same role as does the "volume of the phase space" in Gibbs' theory. Substituting the value for the known constants in the expression for A we find that

$$H(\lambda_1/\lambda)(F_n/F_a^*) = 1.31 \times 10^9.$$

This is an extremely large number compared to the corresponding quantities for simple liquids for which values ≈ 1 are found. It seems most probable that this behavior is due to rather stringent spatial requirements on the moving particle. These requirements mean that the probability of the activated state is much less (apart from energy considerations) than the probability of the normal state. In other words, the moving particle must be favorably oriented. It is also possible that the distance jumped by the moving particle is considerably less than the distance between the moving layers. This would mean that the particle goes a distance much less than its average diameter in the course of a single jump. Probably both these factors are of importance in determining the order of magnitude of the factor A.

The foregoing discussion has neglected entirely the nonhomogeneity of crude rubber. It has been shown by Grenquist, Hauser and Hünemorder, and others,[6] that some of the latex particles of raw rubber persist throughout 60 to 90 minutes of mastication. The present sample had much less breakdown. It seems unlikely that the moving particle can be identified with the latex particle, since we would then expect still larger values for the constant b and smaller values for the constant A. This conclusion is not, however, of great certainty: it would take much more experimental data of the type here discussed in order to settle the question. In particular, it would be desirable to follow the change in the

[5] R. H. Fowler, *Statistical Mechanics* (Cambridge University Press, 1929).

[6] E. A. Grenquist, Ind. Eng. Chem. **21**, 665 (1929); E. A. Hauser and M. Hünemorder, Kautschuk **5**, 151 (1929).

constants of Eq. (5) with mastication of the rubber, and also to determine them for purified rubber.

That these calculations definitely indicate a moving particle larger than the rubber molecule might be cited as evidence for the existence of the much discussed rubber micelle. Such a citation seems unjustified, if we adopt a more reasonable definition of the term "micelle" than is generally used. This is, of course, an arbitrary matter, since there is no well-defined usage for this term. In its broadest sense, a micelle is defined as a clump of molecules held together by van der Waals forces. If we use this definition, it is necessary to regard water as a micellar liquid, and therefore as a colloidal system. This seems a thoroughly unjustifiable extension of the domain of colloidal chemistry, not because of any desire to limit the boundaries of this field of knowledge, but because of the fact that "colloidal" methods of experimentation and discussion have not yielded results of benefit in the investigation of associated liquids. It seems preferable to delimit the colloidal field, and the term micelle, to systems which are definitely of a two phase nature, and to employ those statistical methods which have been fruitful in other fields in an attack upon associated one phase systems, whether they be composed of one or many components.

Under the present interpretation, the rubber hydrocarbon is an associated organic liquid. The association, however, is not caused by intense van der Waals forces, as is the case with water and other simple fluids, but is due to the mechanical interlocking of the long hydrocarbon chains. Association in high polymeric hydrocarbons is therefore a secondary effect of the primary valence forces, and does not depend primarily on van der Waals forces. Regarding the plastic phenomena of rubber from the point of view of the molecular constitution of this substance, it seems most natural that the molecules of raw rubber should be so much entangled that they move as groups or clusters.

The fact that the data obtained by Mooney for the lowest shearing stress do not agree with the theory, is probably to be ascribed to changes in the rubber produced by the shearing stress. It is to be noted that the activation energy under these conditions is correctly given by Eq. (5), since the calculated line is closely parallel to the observed points. The factor A is too small to give agreement with experiment, however, by a factor of about two. This may be due to a partial orientation by the shearing stress of the rubber as a whole. In order for this explanation to hold, it is necessary for the partial orientation to be more complete at the higher shearing stresses than at the lowest. Such a behavior would not be particularly surprising. An alternative explanation may be that the moving particles are partly broken up at the higher shearing stresses so that the quantity λ_1, of Eq. (7) is decreased.

Another way of accounting for the experimentally found increase of A at the lowest shearing stress, would be to assume that the distance jumped increases with increasing stress. If this behavior becomes pronounced, the particle can no longer settle down into the next energy minimum: one or more minima must be passed over. When this is the case the present theory is inadequate to account for the behavior of the system, since under these circumstances viscous resistance by momentum transfer becomes important. This process is familiar from the customary analysis of the viscosity of gases. With a slight revision of the mental picture (free path < molecular diameter) it may be applied to liquids. This has been done by Jaeger and, more recently, by Andrade.[7] Between the limiting cases of very high and very low stresses there will be, of course, a transition region. From the data now under discussion it is not possible to specify just where this transition from viscous loss by activation to loss by momentum transfer takes place for rubber. It is quite probable, however, that it occurs within the higher stresses used in the experiments. To settle questions of this type will require a theory taking account of both activation and momentum transfer. The omission of the latter phenomenon in the present theory accounts for the prediction of Eq. (5) that the viscosity becomes zero at very high stress. This can hardly be expected to be the case.

[7] E. N. daC. Andrade, Phil. Mag. **17**, 497, 698 (1934).

Throughout these calculations the jumping of molecules in the direction opposite to that of the applied stress has been neglected. This seems hardly justifiable at the lowest temperature and stresses, since here $(bf)/T$ is only about 1.3. Substitution of the hyperbolic sine for the exponential term (use of Eq. (4) instead of Eq. (5)) brings the topmost curve of Fig. 1 slightly closer to the experimental points but does not remove the discrepancy. It is interesting, however, that these measurements extend nearly to the range in which it is necessary to consider the reverse flow as well as the forward flow.

A further point to be noticed is that the present treatment assumes that the number of activated particles is not so large that their motion disturbs the thermal equilibrium of the system. There is no *a priori* way of calculating the range of validity of this assumption. From chemical reaction velocities it seems fairly safe in the present application, but if it were not, the system would be in the transition region discussed above and Eq. (5) would not apply.

In conclusion, we may say that Eyring's equation is a satisfactory first step in giving a kinetic description of the viscosities of non-Newtonian systems such as rubber. It is to be hoped that an extension of the theory will be possible.

I wish to express my thanks to Drs. M. Mooney and R. H. Gerke for a number of discussions concerning this work, and to Dr. W. A. Gibbons, director of these laboratories, for permission to publish this paper.

SUMMARY

1. Eyring's equation for the viscosity of a non-Newtonian fluid describes Mooney's data satisfactorily for all except the lowest shearing stress.

2. From the standpoint of the present theory, the behavior at low shearing stresses may most readily be explained by any of the following assumptions: (1) the moving particle is larger at low shearing stresses than at high, (2) the rubber as a whole is less oriented by the lower shearing stress, (3) the distance "jumped" at the low shearing stress may be less than that at high stresses.

3. According to the present interpretation the moving particle (corresponding to the molecule of a simple liquid) is larger than the rubber molecule. It does not seem profitable to interpret this finding as evidence for the existence of a rubber micelle.

4. Both the activation energy of viscous flow for this particular sample of rubber and the factor determined by the spatial requirements which must be fulfilled by the moving particle are much larger than the analogous quantities for low molecular hydrocarbons.

New scientific developments will continue to be born. If necessary, they will come out of barns or garrets, but they will appear. The only possible question is how often will they occur and how fast will they grow. That is where organized, or industrial, research comes in. It accelerates the pace of progress. Scientific problems are not solved by a fine new building and expensive equipment; but, with the many different phases of modern research work, there are definite advantages in a group attack on a project. One man can profit by the experience of others. There will always be opportunities to contribute to progress and human welfare, and the industrial research laboratories of the future I feel sure will do more than their share in this direction.—CHARLES F. KETTERING.

("Research and Industry," *Scientific American*, May 1937)

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American Physics Teacher

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Graduate Preparation for a Career in Physics. pp. 97–101. ***G. P. Harnwell***

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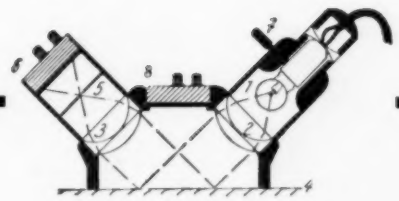

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